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Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021)

organized by the APS Division of Particles and Fields

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This volume is dedicated to the memory of

Meenakshi Narain (1964-2023),

in honor of her many contributions to Snowmass 2021.

Foreword

In 2019, with the construction of the projects supported by the 2014 P5 process well underway or in an advanced stage of planning, the Division of Particle and Fields (DPF) of the American Physical Society (APS) began to prepare a new community study of U.S. high energy physics (HEP) for the decade of 2025 – 2035, and beyond. This "Snowmass 2021" HEP Community Planning Exercise began formally with a kick-off meeting at the 2020 APS April Meeting and a Community-wide Planning Meeting in October of 2020. The exercise was to conclude in July of 2021 with a workshop in Seattle hosted by the University of Washington. The COVID-19 pandemic severely disrupted these plans. Work was paused from January to September of 2021 to lighten the burden on our younger scientists. We resumed work by September of 2021 and, despite the continuing challenges of COVID-19, our community was well prepared for the Seattle meeting, which had been rescheduled for July 17–26, 2022.

Snowmass 2021 was organized into ten working groups, or "Frontiers": Accelerator (AF), Community Engagement (CEF), Computational (CompF), Cosmic (CF), Energy (EF), Instrumentation (IF), Neutrinos (NF), Rare Processes and Precision Measurements (RPF), Theory (TF), and Underground Facilities and Infrastructure (UF). These Frontiers comprise a broad array of ground-breaking research topics and the underlying technology and infrastructure to execute them. CEF explored how the U.S. HEP community can be more representative of and responsive to all its members and can engage with society as a whole.

This report is organized so it can be read at three levels of detail. An Executive Summary presents briefly the vision for the next decade and beyond, the high-level conclusions, and the projects that are proposed to realize the vision. The first chapter summarizes the whole report, including briefly the work of the ten Frontiers. This is followed by ten chapters, one for each Frontier, giving the details of its work, and a chapter on the work of the organization of Snowmass Early Career Scientists. Another chapter discusses the cross-cutting topic of searches for dark matter. The full set of Frontier reports, Topical Group reports, and contributed white papers can be accessed at: https://www.slac.stanford.edu/econf/C210711/.

We thank the host institutions of all of the preparatory meetings, virtual and in-person, leading up to the Snowmass Community Summer Study in Seattle, and especially the University of Washington for their efforts in hosting the July 2022 meeting. We thank four APS Divisions, Astrophysics, Nuclear Physics, Gravitational Physics, and the Physics of Beams, for their help in guiding the study. We are grateful for the financial support of DOE and NSF that enabled a broad and inclusive participation in the Seattle meeting and several all-frontier meetings, and for the helpful collaboration of the APS. We thank Michael Peskin for his valuable help in preparing these proceedings. Finally, we thank the Snowmass community of several thousand people, including international and cross-disciplinary participants, who produced great physics studies despite the challenges of this period.

DPF Chair-line (2022): Joel N. Butler, R. Sekhar Chivukula, André de Gouvêa, Tao Han, for the Snowmass Steering Group and Conveners

Executive Summary

This volume presents the main conclusions of the 2021 HEP Community Planning Exercise, also known as "Snowmass 2021" or just "Snowmass", the most recent of the planning exercises of the U.S. High Energy Physics (HEP) Community, which was sponsored by the Division of Particles and Fields (DPF) of the American Physical Society (APS). The objective of Snowmass 2021 was to examine the status and scientific goals of U.S. HEP and to propose essential scientific programs to pursue and thereby provide community input to the 2023 DOE/NSF "Particle Physics Project Prioritization Panel" (P5), a subpanel of the High Energy Physics Advisory Panel (HEPAP) charged with updating the strategic plan for U.S. HEP for the coming decade and beyond. In addition, the conclusions of Snowmass 2021, especially in the areas related to early career physicists and to community engagement, go beyond those that can be implemented solely by funding agencies — and will also require effort by individuals, universities, laboratories, and national scientific organizations, such as APS and DPF.

Several thousand people contributed to Snowmass 2021. Over five hundred contributed papers (also known as "white papers") were produced. The Snowmass planning process incorporated input from other national and international planning exercises, notably the European Strategy for Particle Physics. The final discussions of all the white papers and other materials developed for Snowmass took place at the Community Summer Study and Workshop at the University of Washington in Seattle, from July 17 – 26, 2022, with an in-person attendance of about 700 and about 650 remote participants.

Snowmass 2021 was organized into ten working groups, or "Frontiers": Accelerator (AF), Community Engagement (CEF), Computational (CompF), Cosmic (CF), Energy (EF), Instrumentation (IF), Neutrino (NF), Rare Processes and Precision Measurements (RPF), Theory (TF), and Underground Facilities and Infrastructure (UF). These Frontiers comprise a broad array of ground-breaking scientific research topics and the underlying technology and infrastructure needed to execute them, as well as, guided by the CEF, a forum to examine how the U.S. HEP community can become more representative of and responsive to all members of our community and can engage with society as a whole. Each Frontier divided its work among several subgroups, known as Topical Groups (TGs) and synthesized the input received from its TGs into a Frontier summary report. In addition, a Snowmass Early Career (SEC) organization was formed to assist young physicists in contributing to the Snowmass process and to bring their issues into the community study. The ten Frontier reports and the SEC Summary Report are included in the full Snowmass Report.

The High Energy Physics Landscape in 2022

After decades of pioneering explorations and milestone discoveries, the Standard Model (SM) of particle physics has been confirmed as the theory that describes electroweak and strong interactions up to energies of a few hundred GeV with great accuracy. However, the SM also leaves several fundamental questions unexplained such as the details of the evolution of the early universe, the origin of the matter-antimatter asymmetry of the universe, the nature of dark matter and dark energy, the origin of neutrino masses, the origin of the electroweak scale, and the origin of flavor dynamics. The answers to these questions must lie in physics beyond the SM (BSM physics). The quest for BSM physics, which has always been on the agenda, is now more than ever the motivating force in particle physics, leading to many proposals for experiments to directly search for new phenomena. Precision measurements of SM processes continue to have a strong place in the program, since these measurements can reveal discrepancies between theory and experiment that can indicate BSM physics, potentially at even higher mass or energy scales than can be observed directly.

A vast range of ideas was considered to probe the boundaries of the SM and to search for BSM physics during the Snowmass 2021 study. The framework for these considerations was provided by the five science

Drivers identified by P5 in 2014:

1. Use the Higgs Boson as a Tool for Discovery,
2. Pursue the Physics Associated with Neutrino Mass,
3. Identify the New Physics of Dark Matter,
4. Understand Cosmic Acceleration: Dark Energy and Inflation,
5. Explore the Unknown: New Particles, Interactions, and Physical Principles.

One important aspect of Snowmass 2021 was to evaluate, after nearly ten years, whether these Drivers continue to be appropriate and complete and can provide guidance for HEP for at least another decade.

The Frontiers Look to the Future

Here we present highlights from the discussions from each Frontier including the most significant projects and programs that each wants to carry out, or at least start, in the next two decades, and the most important conclusions reached concerning enabling technologies and infrastructure. *All* of the particle-physics-focused Frontiers (CF, EF, NF, RPF, and TF) are directly engaged in probing the boundaries of the SM and searching for BSM physics, and the contributions of *all* the enabling Frontiers (AF, CEF, CompF, IF, and UF) are crucial for them to succeed, as can be seen below.

The Cosmic Frontier (Science Drivers 2 – 5): The Cosmic Frontier is focused on understanding how elementary particle physics shapes the behavior and evolution of the universe, and how observations of the universe inform our understanding of physics beyond the Standard Model. In the moments just after the Big Bang, fundamental physics governs the production of the particles and energy fluctuations that give rise to the current universe. The properties of elementary particles also govern the behavior of the most energetic processes observed in the universe today, including supernovas.

A major thrust of the future Cosmic Frontier program is building the next generation of cosmological probes. Cosmic surveys "aim high" at observables spanning almost the entire 13.8 billion-year history of our Universe. The next big project in this arena is CMB-S4, a system of telescopes to study the cosmic microwave background with higher precision than has been achieved so far. CMB-S4, which is expected to operate through to at least 2036, will address many topics, including the mystery of cosmic inflation. Additional projects that would start after 2029 are Spec-S5, the follow-on spectroscopic device to DESI; a project to carry out line intensity mapping (LIM); and planning efforts to increase the sensitivity of gravitational wave detection by at least a factor of 10 (10^3 in sensitive volume) beyond what will be achieved by LIGO/Virgo and their planned upgrades.

A second thrust of the Cosmic Frontier is a suite of experiments to explore the physics of dark matter (DM). The space of DM models encompasses a dizzying array of possibilities representing many orders of magnitude in mass and couplings, making the DM program one of the most "interdisciplinary" investigations in high-energy and particle physics. The Cosmic Frontier's DM program will "delve deep, search wide" by employing a broad portfolio of small and medium-scale, direct and indirect, detection experiments, as is required to search optimally for each decade in dark matter mass. Furthermore, the expanded Cosmic Probes program

described above will strive to identify the properties of dark matter via cosmic surveys, which is highly synergistic with the other science targeted by those surveys.

The Cosmic Frontier strategy detailed in this report encompasses a science-rich program with small, medium, and large experiments which are planned on both near-term and long-term timescales. The community consensus is that this coming decade must feature strong support for this program in full to ensure that HEP will enjoy the new era of discovery and groundbreaking precision measurements.

The Energy Frontier (Science Drivers 1 – 3 & 5): The Energy Frontier currently has a top-notch program with the Large Hadron Collider (LHC) and its planned High Luminosity upgrade (HL-LHC) at CERN, which sets the basis for the Energy Frontier vision. The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no obvious and unambiguous signal of BSM physics. This implies that new physics either occurs at scales higher than we have probed, must be weakly coupled to the SM, or is hidden in backgrounds at the LHC. The immediate goal for the Energy Frontier is to continue to take and analyze the data from LHC Run 3, which will go on for about three more years, and carry out the 2014 P5 recommendations to complete the HL-LHC Upgrade and execute its physics program. The HL-LHC will measure the properties of the Higgs Boson more precisely, probe the boundaries of the SM further, and possibly observe new physics or point us in a particular direction for discovery.

A new aspect of the proposed LHC program is the emergence of a variety of auxiliary experiments that can use the interactions already occurring in the existing collision regions during the normal LHC and HL-LHC running of the ATLAS, CMS, LHCb, and ALICE experiments to explore regions of discovery space that are not currently accessible. These typically involve observing particles in the far forward direction or long-lived particles produced at larger angles but decaying far outside the existing detectors. These are mid-scale detectors in their own right and provide room for additional innovation and leadership opportunities for younger physicists at the LHC. The EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.

New colliders are the ultimate tools to extend the EF program into the next two decades thanks to the broad and complementary set of measurements and searches they enable. With a combined strategy of precision measurements and high-energy exploration, future lepton colliders starting at energies as low as the Z-pole up to a few TeV can shed substantial light on some of these key questions. It will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond. The EF supports a fast start for the construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs Factory will require an immediate, vigorous, and targeted accelerator and detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.

Finally, the U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with, for example, CERN.

The Neutrino Frontier (Science Drivers 2, 3 & 5): Neutrinos, the neutral electroweak partners of the charged leptons, are predicted to be massless in the Standard Model. The demonstration that neutrinos oscillate and therefore have mass is currently the only laboratory observation of BSM physics. The study of neutrinos and their properties is, therefore, an essential component of the U.S. HEP program in the coming decades.

The Deep Underground Neutrino Experiment (DUNE) collaboration was formed to realize the 2014 P5 vision of a best-in-class long-baseline neutrino experiment based at Fermilab. The DUNE R&D program, propelled by the development of large-scale liquid-argon detectors in the U.S. and Europe, in particular through the CERN Neutrino Platform, has demonstrated the power and feasibility of this technique. DUNE will be built in two phases. Phase I includes the completion of the Long-Baseline Neutrino Facility (LBNF) at FNAL and construction at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. This first phase includes far-site facilities at SURF to accommodate four far detector modules (FDs) at a depth of 1475 m (each with at least 10-kt fiducial mass) and installation of the first two FD modules; near-site facilities at FNAL to support the full (Phase II) near detector and installation of a basic suite of near detectors; and the construction of the PIP-II 1.2 MW source proton beam, also at FNAL, to produce a neutrino beam to SURF. The Phase I configuration is sufficient for early physics goals, including the determination of the neutrino mass ordering.

DUNE Phase II is required to achieve the precision neutrino oscillation physics goals laid out by P5 in 2014 and is the U.S. HEP neutrino community's highest priority project for 2030–2040. The Phase II project has three components: an upgrade or replacement of the Fermilab 8 GeV Booster to enable a more intense neutrino beam by delivering 2.4 MW to the DUNE target and possibly to provide beams for other experiments; the construction of an additional 20 kt (fiducial) of far detectors at SURF; and the full, highly capable, near-detector complex at FNAL to control the systematic uncertainties for the far-detector measurements. The full DUNE program will perform definitive studies of neutrino oscillations, test the three-flavor paradigm, search for new neutrino interactions, resolve the mass ordering question, have the ability to observe CP violation if it is present in neutrino oscillation, and observe astrophysical neutrinos.

A suite of small- and medium-scale neutrino experiments can address issues that are complementary to those studied by long-baseline experiments, such as measurements of the absolute neutrino mass and searches for neutrinoless double beta decay. All of these efforts have the potential to make paradigm-changing discoveries or innovations or provide necessary inputs to experiments that will make these discoveries, and they will work in synergy to address the science questions described above. A future neutrino program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.

The Rare Processes and Precision Measurements Frontier (Science Drivers 3 & 5): The Rare Processes and Precision Measurements Frontier encompasses searches for extremely rare processes or tiny deviations from the SM that can be studied with intense sources and high-precision detectors. RPF is currently working on two mid-scale U.S. projects at Fermilab that were endorsed by P5 in 2014, the Muon $g-2$ experiment to measure the anomalous magnetic dipole moment of the muon, which has produced exciting results and is concluding its data-taking; and the Mu2e experiment, currently under construction, which will search for neutrino-less conversion of a negative muon into an electron in the field of a nucleus. The program also has important investments in b-quark, c-quark, and τ-lepton flavor physics through the support of the Belle II experiment at the SuperKEKB accelerator in Japan and the LHCb experiment at CERN. Priorities for the RPF community in the next few years are to complete the $g-2$ analysis; begin taking data with Mu2e; and to continue taking and analyzing data at Belle II and LHCb, and participate in their ongoing and future upgrades. It is worth noting that studies of baryon-number-violating decays of heavy flavors are uniquely being carried out in dedicated flavor experiments, such as LHCb and Belle II.

Two other central themes for the RPF that emerged from Snowmass are the quest to understand quark and lepton flavor and its violation, via precision measurements, and the search for dark-matter production in the mass range from sub-MeV to a few GeV in fixed-target proton and electron experiments. There is a proposal to study muon science in an "Advanced Muon Facility", AMF, at Fermilab, that would greatly

improve the search for lepton flavor violation in $\mu \to e\gamma$, $\mu^- N \to e^- N$, and $\mu \to 3e$. This would require an intense proton beam with unique characteristics and modifications to the FNAL accelerator complex to manage the production of muon beams with different energies and time profiles.

Other experiments under consideration include the measurement of electric dipole moments (EDMs), in particular the proton EDM measurement in a storage ring, along with experiments exploiting techniques developed in the Atomic, Molecular, and Optical (AMO) community to examine fundamental symmetries; experiments probing rare light meson decays; and involvement of the U.S. experimental community in the vibrant international program studying rare kaon decays at both CERN and J-PARC.

As a result of the breadth of flavor physics, its potential for discovering BSM physics, and hints of possible new physics in the current data, the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a new physics driver: *flavor physics as a tool for discovery.*

Theory Frontier (Science Drivers 1-5): Theoretical particle physics seeks to provide a predictive mathematical description of matter, energy, space, and time that synthesizes our knowledge of the universe, analyzes and interprets existing experimental results, and motivates future experimental investigation. Theory connects particle physics to other areas of physics and extends the boundaries of our understanding.

Fundamental theory seeks a deep understanding of the theoretical and mathematical structures that underlie our modern description of Nature and includes directions that are not, or at least not yet, directly connected to experimentally testable consequences. Recently the decades-long search for a theory of quantum gravity has been animated by new insights from string theory and quantum information theory. Progress in quantum field theory and quantum gravity has been tightly intertwined by the revelation of holography, the idea that quantum gravitational physics in a region of space is encoded by a quantum field theory living on its boundary. Promising avenues in the coming decade include the refinement of powerful new perturbative and non-perturbative approaches to quantum field theory, exploration of generalized symmetries and their implications, and a deeper understanding of the emergence of spacetime in the vicinity of black holes.

Particle phenomenology provides the connection between fundamental theory and the physical description of the real world, testable by experiments. The search for BSM physics has broadened considerably in the past decade with the advent of novel concepts like neutral naturalness and cosmological selection of the electroweak vacuum. Significant progress has been made in understanding inflation and properties of the early universe from the cosmic microwave background and large-scale structure. Dark matter theory is undergoing a renaissance with the exploration of the full range of dark matter masses, portals to dark sectors, and novel interaction mechanisms. Advances in precision collider theory, collider phenomenology, and flavor physics (including the calculation of many cross-sections to the next-to-next-to-leading order, the formulation of new collider observables, and advanced theoretical analyses of flavor data) are unlocking the door to unprecedented tests of the SM. And, finally, a theory-driven program combining nuclear theory, lattice and perturbative QCD, and event generation has been launched to quantify nuclear cross sections with the precision needed to realize the full potential of neutrino physics experiments.

Computational theory seeks to quantitatively test our theoretical descriptions of physical phenomena and gain new insights into fundamental aspects of the underlying theories, through developing and deploying computational methods. Over the last decade lattice QCD has become a powerful tool, which provides precise predictions for a broad range of observables relevant to experiment, while lattice methods also provide quantitative access to nonperturabtive properties of new QFTs. Event generators connect experimental measurements to theoretical predictions with increasing accuracy, directly enabling future experimental success. Recent innovations in the theory of machine learning (AI/ML), notable for their cross disciplinary impact, will be profitably utilized in a growing number of theoretical applications, while efforts to develop the

methods and theoretical foundations for quantum simulations of quantum field theories offer great promise for computations of classically intractable problems in the decades to come.

Together, fundamental, phenomenological, and computational theories form a vibrant ecosystem whose health is essential to all aspects of the U.S. HEP program. The Theory Frontier recommends invigorated support for a broad program of theoretical research as part of a balanced HEP portfolio, an emphasis on targeted initiatives to connect theory to experiment, a focus on providing support and training for students and junior scientists, and strengthening the commitment to improve diversity, equity, inclusion and accessibility in HEP theory.

Accelerator Frontier: The Accelerator Frontier aims to prepare for the next generations of major accelerator-based particle physics projects to pursue the EF, NF, and RPF physics goals.

A multi-MW beam-power upgrade of the Fermilab proton accelerator complex is required for DUNE Phase II. Studies are required to understand what other requirements the beam complex needs to meet if the same upgrade is to be used for RPF-related experiments.

In EF, a global consensus for an e^+e^- Higgs Factory as the next collider has been reaffirmed. While some options (e.g. the ILC) have mature designs, other options require further R&D to understand if they are viable. In order to further explore the energy frontier, very high-energy circular hadron colliders and/or multi-TeV muon colliders will be needed, both of which require substantial study to see if construction is feasible in the decade starting in 2040 or beyond. A team of experts formed an "Implementation Task Force" that developed metrics and a process to facilitate a comparison among the many proposed accelerator concepts. Their findings are summarized in part in the Accelerator Frontier Report and are presented in detail in a white paper. It is proposed that the U.S. establish a national integrated R&D program on future colliders to carry out technology R&D and accelerator design studies for future collider concepts.

Community Engagement Frontier: The Community Engagement Frontier concentrated on seven topics: applications and industry; career pipeline and development; diversity, equity, and inclusion (DEI); physics education; public education and outreach; public policy and government engagement; and environmental and societal impacts. The inclusion of this broad array of issues as a "Frontier" was a novel aspect of Snowmass 2021 and led to the formulation of many proposals for consideration and implementation by the community as a whole. These issues impact the ability of all Frontiers to successfully complete their work, and some, such as the need to broaden representation in the U.S. HEP community, were highlighted by all other Frontiers as well. Two additional CEF themes that emerged during the Snowmass process were the need to make HEP activities broadly accessible and sustainable. While many recommendations apply directly to the DOE and NSF programs and could be considered by P5, many are directed to the HEP community as a whole. DPF should consider how best to pursue these issues within APS and with government agencies and other groups.

Computational Frontier: Software and computing are essential to all HEP experiments and many theoretical studies. However, computing has entered a new "post-Moore's law" phase. Speed-ups in processing now come from the use of heterogeneous hardware, such as GPUs and FPGAs developed in the commercial sector, to accelerate calculations, with significant implications for the manner in which we develop and maintain software. We are also beginning to rely on community hardware resources such as High-Performance Computing (HPC) centers and the Cloud rather than dedicated experiment resources. Finally, new machine-learning approaches are fundamentally changing the way we work.

This new computing environment requires substantial changes and novel approaches to address the long-term development, maintenance, and user support of essential software packages, and cross-cutting R&D efforts supported from proof of concept to prototyping and production. Additionally, strong investment in career development for HEP software and computing researchers is needed to ensure future success.

In order to help address these issues, the Computational Frontier recommends the creation of a standing Coordinating Panel for Software and Computing (CPSC) under the auspices of DPF, analogous to the Coordinating Panel for Advanced Detectors (CPAD) established in 2012.

Instrumentation Frontier: Improved instrumentation is key to experimental progress in CF, NF, EF, and RPF. Many aspects of the current instrumentation effort were hardly present in 2013/2014, including quantum sensors, machine learning, and precision timing. Funding for instrumentation in the U.S., however, is actually declining. Key conclusions about how to restore and preserve the instrumentation effort are: to develop and maintain a critical and diverse workforce, including physicists, engineers, and technicians at universities and national laboratories; double the U.S. Detector R&D budget over the next five years and modify existing funding models to enable R&D consortia; expand and sustain support for blue-sky, table-top R&D, and seed funding for pathfinder R&D, and establish a separate review process for these types of activities; and develop and maintain critical facilities, centers, and capabilities for the sharing of common knowledge and tools.

Most of the IF report is dedicated to a review of the status and plans for improving the capabilities of particle detectors and developing new technologies in the following key areas: quantum sensors, photon detectors, solid state detectors and precision tracking systems, triggering and data-acquisition systems, micropattern gaseous detectors, calorimetry, readout electronics and ASICs, noble element detectors, cross-cutting and system integration issues, and radio detection.

The Underground Facilities and Infrastructure Frontier: Experiments that require low backgrounds from cosmic radiation, typically needed by CF and NF experiments, often must be performed underground. Underground experiments address some of the most important questions of particle physics, including the study of dark matter, neutrino physics including neutrinoless double-beta decay and atmospheric neutrinos, cosmic ray physics, and proton decay experiments.

The UF concluded that new experiments and enabling R&D require more space than is currently available worldwide. They proposed a possible addition of the underground space at a depth of 4850 feet at SURF in South Dakota and possible additional space at a depth of 7400 feet. These would open up space to develop additional experiments and would provide the opportunity for SURF to host next-generation dark matter or $0\nu\beta\beta$ experiments.

As underground experiments become larger, they will increasingly have stricter radiation requirements and the need for larger and higher quality clean rooms, radon-reduction systems, and improved monitoring. These issues are discussed in the Underground Facilities Frontier report and information was presented on the needs of upcoming experiments.

Snowmass Early Career: The perspective on HEP in Snowmass 2021 reaches far enough into the future to surpass the timescale of a single career, making consideration of the next generation of physicists crucial. The 2021 Snowmass Early Career organization aimed to unite this group, consisting mainly of graduate students and post-doctoral research associates, with the purpose of educating the newest generation of physicists while informing the senior generation of their opinions, concerns, and needs.

One major activity of the SEC was the Snowmass Community Survey, which was designed by the SEC Survey Core Initiative team between April 2020 and June 2021 with the aim of collecting demographic, career, physics outlook, and workplace culture data on a large segment of the Snowmass community (both junior and senior). A high-level summary of the key findings and recommendations from the survey report can be found in the SEC Summary Report. Early career physicists took the lead in many other areas, including several successful events focused on industry careers, networking, and perspectives. They also hosted community discussions on mental health and invisible disabilities and participated in panel discussions on community topics such as COVID-19 and career development.

The SEC community was very active in the discussions of future directions in HEP and played a strong and influential role in advancing and advocating for recommendations in several areas.

The Path Forward

One of the most important goals of Snowmass 2021 was to develop a vision for the U.S. HEP community for the next decade, with an eye to the decade beyond that, and to identify the infrastructure, facilities, and experiments needed to achieve it. The aspirations of the U.S. HEP community as informed by the Snowmass 2021 process are succinctly summarized as follows:

> *Lead the exploration of the fundamental nature of matter, energy, space and time, by using ground-breaking theoretical, observational, and experimental methods; developing state-of-the-art technology for fundamental science and for the benefit of society; training and employing a diverse and world-class workforce of physicists, engineers, technicians, and computer scientists from universities and laboratories across the nation; collaborating closely with our global partners and with colleagues in adjacent areas of science; and probing the boundaries of the Standard Model of particle physics to illuminate the exciting terrain beyond, and to address the deepest mysteries in the Universe.*

There was broad agreement at Snowmass 2021 on the general principles needed to have a successful U.S. HEP program in the future:

- In 2014, P5 formulated five science Drivers that were meant to summarize and organize the scientific questions that HEP seeks to answer. These five Drivers have guided U.S. HEP for nearly a decade with great success. We have made tangible progress toward addressing them, and have used that progress to formulate the steps for the next decade that are outlined in this report. There was consensus in Snowmass 2021 that these Drivers were still appropriate for the next decade.
  - A proposal was made by the Rare Processes and Precision Measurements Frontier that the physics of flavor, currently included without explicit acknowledgment in the science Drivers, be specifically named, given its unique characteristics and opportunities. One way of accomplishing this would be for flavor physics to become a sixth Driver.
- The completion of existing experiments and the construction and operation of approved projects, including those prioritized by the 2014 P5 such as the HL-LHC, LBNF/DUNE, PIP-II, LSST/Rubin Observatory, and Mu2e programs, along with our many midsize and small experiments, are critical for addressing the science Drivers for the near term and for much of the next two decades.
- As existing approved construction projects come to a completion, a broad and complementary set of new projects should be considered a high priority to maintain the continuity of our investigations and opportunities for new discoveries.

  - A list of the large-scale (estimated total project costs of approximately $500M or larger) new projects or programs discussed at Snowmass is shown in Table 1 of Chapter 1 of the full Report and is described in detail in section 1.2.1 and in the Frontier summaries that follow. The proposals are examined in detail in the Snowmass 2021 Frontier and Topical Group reports.
  - The portfolio of HEP projects should continue to include a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported by a dedicated, robust, ongoing funding process. Medium- and smaller-scale projects are discussed more fully in section 1.2.2 of the full Report, and the corresponding Topical Group reports.

- Robust support for physics research programs at universities and national laboratories is essential to operate existing and planned experiments, analyze the data they collect, plan and construct upgrades and new experiments and projects, and educate the next generation of researchers and technical experts.

- Strong and continued support for all aspects of particle theory, comprising the interconnected themes of fundamental theory, phenomenology, and computational theory, is needed. As theoretical and experimental research are symbiotically entwined, stronger, targeted efforts connecting theory to experiment should also be supported.

- Greater support for the infrastructure and enabling technologies, namely accelerators, computation, detectors, and instrumentation, is essential. Both R&D directed to specific future projects and generic research should be supported in these critical enabling technologies, as well as in new areas such as quantum science and machine learning.

  - Some guidance to HEPAP and the funding agencies in how the work of the enabling Frontiers should be coordinated and advanced would be very valuable.
  - When R&D projects produce successful tools, where appropriate, plans should be developed to convert them to products and support them throughout their useful lives.

- HEP benefits from collaboration with adjacent scientific disciplines, such as nuclear physics, accelerator technology and beam physics, astronomy and astrophysics, gravitational physics, and atomic and molecular physics, and from interactions with industry, and contributes to them in return. Opportunities to strengthen and expand such collaborations are mutually beneficial and should be pursued, and new opportunities for collaboration are arising in other areas such as artificial intelligence and machine learning, and quantum information science and sensing.

- The HEP community should strengthen connections with its early career researchers, foster their professional success both within and outside of academia, and ensure their voices are well-represented in physics and community planning.

- HEP should take a cohesive and strategic approach to promote diversity, equity, and inclusion in high-energy physics, in collaboration with funding agencies, universities, adjacent scientific disciplines, APS/DPF, and others.

  - The community should institute a broad array of practices and programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision and to address the persistent under-representation of women scientists, LGBT+ scientists, scientists who are Black, Indigenous, and people of color (BIPOC), and scientists with disabilities.

- The HEP community must engage in a coordinated way with five other interrelated communities: academia, the education communities providing instruction from kindergarten through postdoctoral training, private industry, government policymakers, and the broader society. A structure for formulating a coordinated approach to achieve these goals should be created and provided with the resources needed for success.

The Snowmass 2021 process highlighted the breadth, depth, and effectiveness of the U.S. HEP program in exploring the fundamental nature of matter, energy, space, and time. The remarkable progress that has been made in probing the boundaries of the Standard Model of particle physics since 2014 was analyzed, and different and complementary methods to move forward in uncovering the mysteries of nature were examined. Through the Snowmass process, the U.S. HEP community has created an integrated vision to make progress in the coming decades – a vision that is reported in detail in this volume, the Topical Group reports, the white papers, and the many references cited therein.

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Summary of the 2021-22 U.S. HEP Community Planning Exercise

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1.1 Introduction

Particle physics seeks to identify the elementary constituents of matter and the forces and principles by which they interact. By looking at matter at the smallest distance scales, physicists have identified the interactions that operate at the subatomic level: the strong, weak, and electromagnetic forces – the last two of which are unified into a single electroweak theory. The force carriers of these interactions, the photon, the W, and Z bosons of the electroweak theory, and the gluons of the strong interactions, along with the quarks and leptons, the fermionic components of matter, form the basis of the Standard Model (SM) of particle physics.

The last missing element in the SM was the agent of electroweak symmetry breaking, which gives mass to the W and Z bosons as well as the quarks and leptons. The new scalar particle discovered at the Large Hadron Collider (LHC) by the ATLAS and CMS experiments in 2012 is produced and decays in a manner that suggested that it is the "Higgs boson", the excitation of an elementary scalar Higgs field which accommodates the simplest mechanism for electroweak symmetry breaking. In the decade since then, ATLAS and CMS have shown that the couplings of this new boson to the heaviest SM particles, the top quark, the tau lepton, and the b-quark, all of which are third-generation fermions, as well as to the W and Z, are all consistent with its interpretation as the Higgs boson. While there is plenty of room for new physics and there is much work to be done to fully study this remarkable, unique scalar particle, its discovery demonstrates that the SM is at least approximately correct and accurately describes elementary particles and their interactions at energies up to a few hundred GeV.

While the SM explains many aspects of the fundamental physics world with impressive accuracy, it is nonetheless silent on several issues of fundamental importance, including the "small" mass, 125 GeV, of the Higgs boson, which is unstable to radiative corrections from interactions at higher energy scales; the excess of

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matter over antimatter (the baryon asymmetry of the universe); why the strong interaction does not exhibit CP violation; the mechanism behind the tiny yet nonzero neutrino masses; the issue of flavor, namely why are there three generations of quarks and leptons with disparate masses and mixings and why is the mixing pattern observed in the lepton sector so different from that in the quark sector; the origin and nature of dark matter and dark energy; the mechanism for cosmic inflation in the early Universe; how gravity fits into the other fundamental interactions and how our general relativistic understanding of space and time can be reconciled with quantum mechanics. These are profound questions whose answers will fundamentally change our understanding of the physical world. Since the answers to these questions cannot be found within the SM, there must be new Beyond the Standard Model (BSM) particles and interactions that explain these aspects of nature.

We have many theoretical ideas that address some or all of these problems but, for now, no unambiguous experimental guidance on which ones are correct. Hints do exist, including the tension between some theoretical calculations of the anomalous magnetic moment of the muon and the measured value, anomalies in neutrino physics exhibited in short-baseline experiments, a possible disagreement between the most recently published, most precise measurement of the W boson mass and its theoretical value, and several anomalies in quark flavor physics. With more and more precise data, some of these may disappear or have explanations within the SM, while others may evolve into puzzles whose solutions provide vital hints about BSM physics. Along the way, new anomalies might emerge, potentially pointing in unforeseen directions. The next big clue may be hiding within data already collected at the LHC or about to be collected during the planned High Luminosity LHC (HL-LHC) era or in the rare decays and properties of known particles. Ongoing or future oscillation experiments may reveal more surprises in the neutrino sector. The new physics may be at masses higher than we can currently reach or weakly coupled enough that it has yet to manifest itself in a way we are prepared to notice.

At present we have come to understand that we are confronted by a vast range of possibilities for BSM physics. For example, the particle that might constitute dark matter can have a mass that spans 90 orders of magnitude. This is an exciting challenge. There is room for innovative ideas and a vast unexplored territory to investigate. There are extraordinary new accelerators and detectors that we can build, new and different observations we can make, along with enormous computing power and new techniques that permit us to collect and analyze unprecedented amounts of data using innovative, more powerful software tools. These new techniques enable us to probe the boundaries of the SM to unprecedented accuracy and extend the search for BSM physics to higher energy scales and weaker couplings. For these reasons, we believe that we will find the trail of the new physics that lies beyond the SM. This will take the efforts, imagination, and creativity of the community that participated in Snowmass 2021, joined by a large and even more diverse new generation of bold thinkers and intrepid doers. We, therefore, present the following vision that emerged from Snowmass:

> *Lead the exploration of the fundamental nature of matter, energy, space and time, by using ground-breaking theoretical, observational, and experimental methods; developing state-of-the-art technology for fundamental science and for the benefit of society; training and employing a diverse and world-class workforce of physicists, engineers, technicians, and computer scientists from universities and laboratories across the nation; collaborating closely with our global partners and with colleagues in adjacent areas of science; and probing the boundaries of the Standard Model of particle physics to illuminate the exciting terrain beyond, and to address the deepest mysteries in the Universe.*

We conclude from our long community study that, in the spirit of Snowmass, we stand ready with great enthusiasm to "delve deep, search wide, and aim high" to advance our understanding of the Universe!

1.1.1 The Snowmass Process, Introduction and History

This report presents the main conclusions of Snowmass 2021, the most recent of the U.S. High Energy Physics (HEP) Community Planning Exercises, sponsored by the Division of Particles and Fields (DPF) of the American Physical Society (APS), with strong consultation from the aligned APS Divisions of Nuclear Physics, Astrophysics, Gravitational Physics, and Physics of Beams. These exercises have occurred roughly every seven to twelve years since 1982. The goal of these community studies has been to identify the most important scientific questions in HEP for the following decade, with an eye to the decade after that, and the facilities, infrastructure, and R&D needed to pursue them. Although focused on the U.S. HEP program, HEP is a global enterprise and international participation was encouraged. Many scientists from outside the U.S. have contributed to Snowmass 2021. HEP has important connections to many other fields of physics and physicists from all related fields have participated. For many years these efforts concluded with a workshop in the summer in Snowmass, Colorado and so these exercises became known as the Snowmass Summer Study and Workshops. The last such exercise was held in 2013 [1]. Its concluding workshop was for the first time held outside of Snowmass at the University of Minnesota. However, we retained the name "Snowmass" to connect it to and commemorate the previous studies.

In 2013 and all previous editions, the planning exercise focused on scientific issues without considering detailed budget constraints or establishing project or funding priorities. All scientifically credible ideas and proposals were welcome. These science exercises were each followed by a subpanel of High Energy Physics Advisory Panel (HEPAP) that advised the funding agencies on which of the many proposed experiments and projects should be carried out, given realistic budget constraints. In 2013, the output of the Snowmass study provided input to the HEPAP subpanel called the Particle Physics Project Prioritization Panel, "P5", which was charged by the U.S. Department of Energy (DOE) and the National Science Foundation (NSF) with the task of recommending plans for U.S. investments in particle physics under specific budget scenarios for the coming decade. P5 began its work in the fall of 2013 and produced a report [2] with its recommendations in the spring of 2014.

At the start of its deliberations, P5 examined the findings of the Snowmass study and identified five main science Drivers for HEP:

1. Use the Higgs Boson as a Tool for Discovery,
2. Pursue the Physics Associated with Neutrino Mass,
3. Identify the New Physics of Dark Matter,
4. Understand Cosmic Acceleration: Dark Energy and Inflation,
5. Explore the Unknown: New Particles, Interactions, and Physical Principles.

It also made 29 recommendations concerning the projects and we have been constructing the favored ones, some of which are shown in Fig. 1-1, since 2015. The two-step approach to planning, the community Snowmass study, centered on the science, and the subsequent P5 prioritization, also taking into account budget constraints, led to a clear understanding and broad acceptance of the 2014 P5 report by the HEP community and beyond.

Among the projects assigned the highest priority by P5 was participation in the High Luminosity Upgrade of the Large Hadron Collider and the ATLAS and CMS experiments at CERN; the LSST/Rubin Observatory; and the construction of PIP-II SRF proton linac at Fermilab and the LBNF/DUNE (Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment) long baseline neutrino experiment. The full suite of

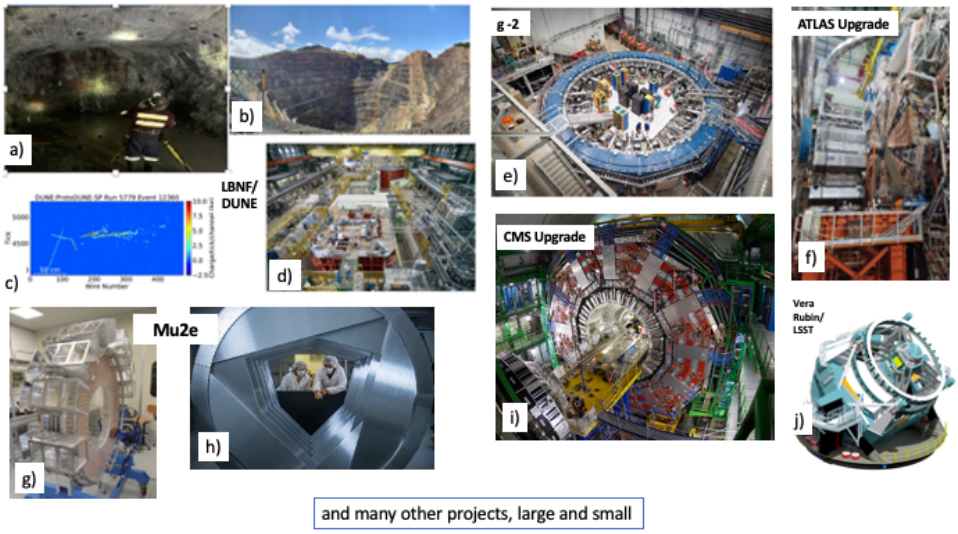

Figure 1-1. *Examples of some of the projects prioritized in the Snowmass 2013/P5 2014 process.* **LBNF/DUNE:** *a) cavern excavation; b) "open cut" to receive excavated rock; c) interactions recorded by Proto-DUNE-SP; d) Neutrino Platform at CERN;* **Muon g-2:** *e) muon storage ring;* **ATLAS Upgrade:** *f) New Small Wheel;* **Mu2e:** *g) calorimeter support frame; h) Tracker planes;* **CMS Upgrade:** *i) Phase 1 upgrade pixel installation;* **Vera Rubin Observatory:** *j) schematic.*

experiments enabled by the projects recommended by the 2013/14 Snowmass/P5 process was chosen to enable U.S. high energy physicists and their partners to examine the properties of matter at the tiniest distance scales ever probed and set the stage for the exciting experimental investigations of the decade just past and into the decade to come.

1.1.2 Introduction to Snowmass 2021

In 2019, with the construction of many of the projects supported by the 2013/14 planning process well underway or in an advanced stage of planning, as shown in Fig. 1-2, the U.S. High Energy Physics Advisory Panel (HEPAP) recognized the need for a new community study to develop the initiatives in the decade starting in 2025. DPF began preparation for Snowmass 2021 community study in 2019. This "Snowmass 2021" HEP Community Planning Exercise formally began with a "kick-off" meeting at the 2020 APS April Meeting and was followed by a Community-wide Planning Meeting (CPM), in October 2020, in which many activities, meetings, and workshops were mapped out. The exercise was to have concluded in July of 2021 with a final workshop in Seattle hosted by the University of Washington. The COVID-19 pandemic severely disrupted our plans and forced us to pause work between January and September of 2021, especially to lighten the burden on our younger scientists, many of whom had to take care of and school their young children. The final workshop in Seattle was delayed until the summer of 2022 and the start of the P5 panel was also delayed by one year by the DOE and NSF. We resumed work for Snowmass in September of 2021 and, despite the continuing, but now diminished, challenges of COVID-19, our community accomplished an amazing amount of work and was well prepared for the Seattle meeting in July of 2022.

Snowmass 2021 was organized into ten working groups, or "Frontiers": Accelerator (AF), Community Engagement (CEF), Computational (CompF), Cosmic (CF), Energy (EF), Instrumentation (IF), Neutrinos (NF), Rare Processes and Precision Measurements (RPF), Theory (TF), and Underground Facilities and Infrastructure (UF). These Frontiers comprise a broad array of ground-breaking scientific research topics and the underlying technology and infrastructure needed to execute them, as well as, through the CEF, a forum to examine how the U.S. HEP community can become more representative of and responsive to all members of our community and can engage with society as a whole. Each Frontier divided its work into several Topical Groups (TGs). The number of TGs varied by Frontier from 6 to 11 and there were approximately 80 overall. A call for two-page "Letters of Interest (LOIs)", due by August 31, 2020, resulted in over 1500 submissions. These were assigned to the TGs (recognizing overlaps). Each Topical Group encouraged its members to produce contributed papers more completely describing their ideas and plans. Often, several submitters of LOIs joined together to produce a single contributed paper. Over five hundred contributed papers, also known as white papers, were produced! The work incorporated input from the "European Strategy for Particle Physics" and other national and international planning exercises.

Early Career physicists have been formally represented at Snowmass since 2001 and gained even more formal recognition in 2013. In 2021/22, a Snowmass Early Career (SEC) organization was formed to assist young physicists in contributing to the Snowmass process and to bring their issues into the community study. The SEC was treated comparably to a full Frontier. There were also important connections among all the Frontiers, and we implemented a strong team of about 80 cross-frontier liaisons to make sure nothing fell between the cracks. International and interdisciplinary participation was encouraged. Our goal was for everyone to be able to participate and for all voices to be heard.

Leading up to the Seattle meeting, both before and after the pandemic pause, there were many TG workshops/meetings, cross-frontier/cross-TG workshops/meetings, and many studies carried out by groups and individuals. By the spring of 2022, nearly 500 white papers had already been submitted. By January 2022, it was possible for people to travel to and attend meetings with a relatively low risk of contracting COVID, and about half the Frontiers held "all-frontier" meetings with both in-person and remote participation, with the other Frontiers relying completely on videoconferencing. The purpose of these meetings was to begin the synthesis of the white papers and the formulation of the topical group reports.

The final discussions and synthesis of all the white papers and other materials developed for Snowmass took place at the Community Summer Study and Workshop (CSS) at the University of Washington in Seattle, from July 17-26, 2022. Vaccines and other measures enabled us to conduct a safe, hybrid meeting, with an in-person attendance of about 700 and about 650 participants connecting remotely, as pictured in Fig. 1-3.

The daily CSS program typically started at 8 am and ran until 7 pm. Days 2-8 were packed with parallel sessions dedicated to Frontier and cross-frontier meetings in the mornings and three 90-minute-long plenary sessions in the afternoons in which each Frontier presented talks designed to inform the entire community of its main plans and conclusions. There were also panel discussions of issues of common interest to the whole community. Day 1 and days 9 and 10 consisted of all-plenary sessions that included special presentations of plans and planning processes by many leaders of U.S. and international institutes, laboratories, and funding agencies. Also, on days 8 and 9, each Frontier summarized its vision for the future and its main conclusions and recommendations, including the projects and facilities that would be needed to realize the vision.

On the final day of the CSS, Priscilla Cushman of the University of Minnesota put it all in perspective with her inspiring talk, "Snowmass Highlights and Message Distillation". As the audience held its breath, JoAnne Hewett of SLAC National Accelerator Laboratory and chairperson of the U.S. High Energy Physics Advisory Panel, announced that the new P5 chairperson is Hitoshi Murayama from UC Berkeley.

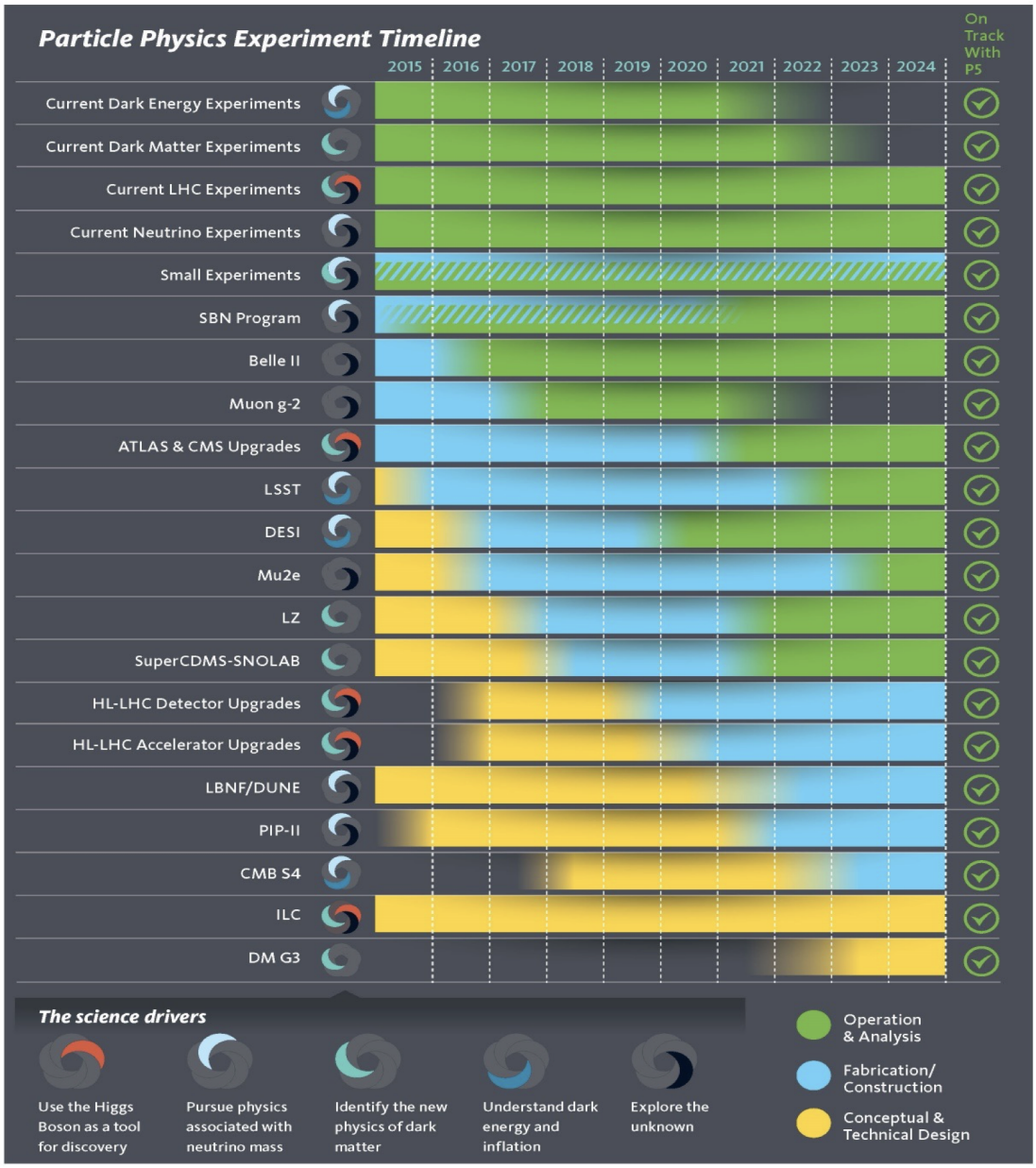

Figure 1-2. *Status of projects supported all or in part by DOE in operation (green), under construction or in production (blue), or still under design and project definition (yellow), shown at the Snowmass Community Summer Study, July 2022.*

Figure 1-3. *Snowmass Community Summer Study, University of Washington, Seattle, a photograph showing in-person attendees in the center and panels in the upper right- and left-hand corners showing some of the remote participants.*

A full schedule for the Seattle meeting, along with talks and eventually recordings, can be found on the Snowmass Indico site [3]. The Frontier Summaries and related documents [4–15] are included in this volume.

1.1.3 Overview of the Snowmass Report

This report represents the summary of the Snowmass 2021 Community Planning Exercise. It is organized around the work of the ten Frontiers and the SEC. Each Frontier and the SEC conducted its work in meetings of various kinds, mostly using Zoom because of COVID-19, but with some hybrid meetings with an in-person component as the pandemic began to abate in the spring of 2022. By the late spring, the Topical Groups in each Frontier and the SEC began preparing their reports. All participants in the work were encouraged to read and comment on the various drafts. Revisions were made and eventually, a final consensus report emerged. By the time of the CSS, Topical Group reports of each Frontier were being synthesized into Frontier Reports. These also went through a process of drafting, followed by meetings, commentary, and iteration to achieve a consensus.

The remainder of this Chapter consists of some very high-level conclusions, a discussion and assessment of the five science Drivers defined by P5/2014 and their applicability to HEP in the next decade and beyond, a brief summary of each of the ten Frontier reports and the SEC report, some examples of cross-cutting HEP activities, and some concluding observations.

In the full Snowmass Report, this summary chapter is followed by eleven chapters, the ten Frontier reports and the SEC report. These are followed by a chapter that discusses the search for dark matter as an example of how the Frontiers are working together, and with adjacent disciplines, to solve one of our most important puzzles. Finally, there is a brief summary and conclusion for the whole Snowmass process. Key contributors are acknowledged at the end of the report.

1.2 High-Level Conclusions from Snowmass 2021

There was broad agreement at Snowmass 2021 on the general principles needed to have a successful U.S. HEP program in the future.

- In 2014, P5 formulated five science Drivers that were meant to summarize and organize the scientific questions that HEP seeks to answer. These five Drivers have guided U.S. HEP for nearly a decade with great success. We have made tangible progress toward addressing them, and have used that progress to formulate the steps for the next decade that are outlined in this report. There was consensus in Snowmass 2021 that these Drivers were still appropriate for the next decade.
  - A proposal was made by the Rare Processes and Precision Measurements Frontier that the physics of flavor, currently included without explicit acknowledgment in the science Drivers, be specifically named, given its unique characteristics and opportunities. One way of accomplishing this would be for flavor physics to become a sixth Driver.
- The completion of existing experiments and the construction and operation of approved projects, including those prioritized by the 2014 P5 such as the HL-LHC, LBNF/DUNE, PIP-II, LSST/Rubin Observatory, and Mu2e programs, along with our many midsize and small experiments, are critical for addressing the science Drivers for the near term and for much of the next two decades.
- As existing approved construction projects come to a completion, a broad and complementary set of new projects should be considered a high priority to maintain the continuity of our investigations and opportunities for new discoveries.
  - A list of the large-scale (estimated total project costs of approximately $500M or larger) new projects or programs discussed at Snowmass is shown in Table 1-1 and is discussed in section 1.2.1 and in the Frontier summaries that follow. The proposals are examined in detail in the Snowmass 2021 Frontier and Topical Group reports.
  - The portfolio of HEP projects should continue to include a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported by a dedicated, robust, ongoing funding process. Medium- and smaller-scale projects are discussed more fully in section 1.2.2, the reports in this volume, and the corresponding Topical Group reports.
- Robust support for physics research programs at universities and national laboratories is essential to operate existing and planned experiments, analyze the data they collect, plan and construct upgrades and new experiments and projects, and educate the next generation of researchers and technical experts.
- Greater support for the infrastructure and enabling technologies, namely accelerators, computation, detectors, and instrumentation, is essential. Both R&D directed to specific future projects and generic research should be supported in these critical enabling technologies, as well as in new areas such as quantum science and machine learning.
  - Some guidance to HEPAP and the funding agencies in how the work of the enabling Frontiers should be coordinated and advanced would be very valuable.
  - When R&D projects produce successful tools, where appropriate, plans should be developed to convert them to products and support them throughout their useful lives.
- HEP benefits from collaboration with adjacent scientific disciplines, such as nuclear physics, accelerator technology and beam physics, astronomy and astrophysics, gravitational physics, and atomic and

molecular physics, and from interactions with industry, and contributes to them in return. Opportunities to strengthen and expand such collaborations are mutually beneficial and should be pursued, and new opportunities for collaboration are arising in other areas such as artificial intelligence and machine learning, and quantum information science and sensing.

- The HEP community should strengthen connections with its early career researchers, foster their professional success both within and outside of academia, and ensure their voices are well-represented in physics and community planning.
- HEP should take a cohesive and strategic approach to promote diversity, equity, and inclusion in high-energy physics, in collaboration with funding agencies, universities, adjacent scientific disciplines, APS/DPF, and others.
  - The community should institute a broad array of practices and programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision and to address the persistent under-representation of women scientists, LGBT+ scientists, scientists who are Black, Indigenous, and people of color (BIPOC), and scientists with disabilities.
- The HEP community must engage in a coordinated way with five other interrelated communities: academia, the education communities providing instruction from kindergarten through postdoctoral training, private industry, government policymakers, and the broader society. A structure for formulating a coordinated approach to achieve these goals should be created and provided with the resources needed for success.

1.2.1 Large-Scale Future Proposals Discussed at Snowmass 2021

Although costs and budgets of future projects or programs were not considered in detail during the Snowmass process, the new proposals discussed were divided into categories based on the approximate total projected cost – "large", greater than ∼$500M, "medium", between of order $75M−$500M, and "small", less than or of order $75M.[1] The identification of large proposals, and their related timescales, is particularly important for the combined Snowmass/P5 process since the impact that they have on planning is so significant. In contrast, "medium" and "small" projects and proposals, though extremely important, of great scientific value, and essential to maintain the diversity and vibrancy of the U.S. HEP program (see section 1.2.2), have a much smaller effect on overall resources. In Table 1-1 we list the future large proposals discussed during the Snowmass process for the coming two decades to address the essential scientific goals that were identified.

As illustrated in Table 1-1, the future large-scale projects/programs that were discussed during Snowmass 2021 fall into four scientific themes – broadly corresponding to the scientific questions addressed by the energy, neutrino, cosmic, and rare process Frontiers – and can be classified as occurring in the coming decade or the following one. The specific scientific goals and capabilities of the projects included in this table are discussed further in this document and the Frontier Reports that follow – and even more thoroughly in the related Topical Group Reports. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. The projects listed were considered during Snowmass 2021 without prioritization or consideration of any future budget scenarios.

Some notes on each of the scientific categories in the table:

[1] These monetary thresholds were used in the Snowmass study for discussion purposes only, and are not aligned with any budgeting process. The costs are intended to represent the U.S. share of the projects.

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

- In the Cosmic Frontier, a coordinated multi-scale dark matter program would combine direct, indirect, and cosmic probe experiments to explore the large dark-matter landscape (and, in total, rise to the "large" project category). Note that an expansion of underground facilities at SURF may be required as a component of this program. In the observational Cosmic program, projects may leverage funding from sources outside of HEP itself, as denoted by the asterisks in the table. Both CMB-S4 and Gen-3 WIMP searches (previously DM-G3) were endorsed as promising future directions by the previous Snowmass/P5 process.

- In the case of the Energy Frontier, and as emphasized by the Accelerator and Theory Frontiers as well, the goal should be to position the U.S. HEP program to support construction of an Higgs Factory as early as 2030, and to subsequently be prepared to host or participate in the construction of a multi-TeV (muon or hadron) collider. In total, these investments (referred to as a "U.S. Initiative for the Targeted Development of Future Colliders and their Detectors" in Table 1-1) rise to the level of a large-scale project. In the early phase accelerator work should prioritize an e^+e^- Higgs Factory (such as ILC, CLIC, FCC-ee, CEPC, C^3, or HELEN), a parallel effort should focus on multi-TeV colliders for the longer term, and some work on advanced accelerator R&D should continue. Targeted detector R&D for the Higgs Factory is required in the early phase, with a smaller detector R&D component related to multi-TeV colliders. In the later phase, as an e^+e^- Higgs Factory construction is taking place, accelerator and detector R&D effort on multi-TeV colliders will need to increase.

- For the Neutrino Frontier the highest priorities are the completion of LBNF/DUNE Phase I in the coming decade (with the corresponding PIP-II upgrade), and the construction of DUNE Phase II (with the corresponding proton source upgrade) in the decade following. DUNE Phase I and Phase II are described briefly in section 4.7 and more completely in the Neutrino Frontier report. The completion of the DUNE science program was identified as a high priority of the previous Snowmass/P5 process.

- For the Rare Process and Precision Measurements Frontier, the "Advanced Muon Facility" for studies of muon decays, muon conversion, and muonium transitions, may require coordinated improvements or modifications to the FNAL proton complex.

1.2.2 Medium- and Small-Scale Future Experiments and Projects

Medium- and small-size experiments and projects are an important component of the current and proposed program. In the past, experiments with these scales have made significant measurements and important discoveries, opening up new areas of scientific exploration. Furthermore, because of their timescale and size, these experiments offer unique leadership and training opportunities for younger physicists and allow for greater diversity in the experimental particle physics ecosystem.

In the Snowmass process, many medium- and small-scale experiments have been presented – too many and too diverse a group to easily categorize and summarize. Here we mention a few broad classes corresponding to the four major experimental directions, though this list is not comprehensive.

- **Cosmic Frontier:** Many small- and mid-scale dark matter searches are needed to cover the huge parameter space, including models of ultralight dark matter such as the QCD axion, in which dark matter could reside. Various expansions of astroparticle observatories such as IceCube Gen2, AugerPrime, the Cerenkov Telescope Array, and the Southern Wide-field Gamma Ray Observatory are also underway or planned, to probe fundamental physics beyond accelerator energies. While mostly supported outside of DOE, these can benefit HEP by probing fundamental physics in regimes not accessible to accelerators.

- **Energy Frontier:** A series of medium-scale "auxiliary experiments" are being pursued using the products of collisions that will already be available in the ATLAS, CMS, and LHCb interaction regions to study parts of phase space that are not covered by those experiments. Examples of experiments being considered include: FASERν, Mathusla, CODEX-b, FACET (a forward extension of CMS), and those associated with the Forward Physics Facility (FPF).

- **Neutrino Frontier:** A case was made at Snowmass for a comprehensive short-baseline neutrino program; a program to measure many basic neutrino scattering processes that we have never before been able to measure precisely; a campaign to measure the proton-nucleus cross sections needed to understand fluxes in neutrino beams; a search for new neutrino interactions; the use of astrophysical neutrinos as messengers of physics and astrophysics; and several other topics.

- **Rare Processes and Precision Measurements Frontier:** Upgrades are proposed to two projects to study b-quarks in which the U.S. currently participates, LHCb at CERN and Belle II at KEK in Japan. The U.S. community working in heavy-flavor physics has a long tradition of leadership and innovation. LHCb is currently commissioning its Upgrade I, which features an innovative purely software trigger, and is planning a second upgrade that should lead to an even higher sensitivity and a broader physics reach in the HL-LHC era. Belle II and SuperKEKB are considering staged upgrades to reach higher luminosity. Individually and even more in combination, the synergistic efforts of LHCb and Belle II will lead to an unprecedented breadth of exploration of heavy quark physics as a tool of discovery. The pair add unique studies of rare tau decays, exotic QCD states, and other fundamental quantities with an overall program that spans our Frontier.

  New projects are proposed to study the decays of particles containing light or strange quarks, charged lepton flavor experiments to study flavor violation and lepton flavor non-universality, and dark sector beam dump experiments to search for new feebly-interacting particles. Additional directions discussed include an upgrade to the Mu2e experiment, and the development of storage rings to search for a proton electric dipole moment.

A balanced portfolio of these mid- and small-scale experiments from all four Frontiers is a vital component of a healthy and vibrant U.S. HEP program. An important recommendation of Snowmass is that resources

be allocated to allow for a sufficiently large and diverse selection of important small- and medium-scale experiments to go forward in the coming decade.

1.3 A Science Driver-Oriented View

These are exciting and challenging times for fundamental particle physics. During the last several decades of intense experimental and theoretical research, we have come to rely on the Standard Model of particle physics — a very predictive, relativistic, spontaneously-broken quantum gauge field theory — in order to describe microscopic phenomena at the smallest accessible distance scales and highest accessible energy scales. Its most remarkable prediction – the existence of a Higgs particle associated with a fundamental scalar field responsible for electroweak symmetry breaking – was established in the last decade, while innumerable other nontrivial predictions and relationships have been confirmed, sometimes with extraordinary precision.

There are, however, big questions in fundamental particle physics to which we currently do not know the answer. These cannot be addressed with the current version of the SM and call for new particles, new interactions, and, perhaps, a qualitatively different description of nature at very small distance scales. There are several potential answers, but at this point, we know very little about these potential new particles and interactions. There are different research directions and inquiries we expect, in tandem, to guide the way. These were organized by the last P5 into science Drivers [2]. Here, we make use of the science Drivers in order to discuss the progress made on the big questions in particle physics over the last decade and to guide the research directions particle physics should pursue in this decade. In the last subsection, we present a proposal from the Rare Process and Precision Measurements Frontier to highlight the physics of flavor, possibly as another Driver.

1.3.1 Use the Higgs Boson as a Tool for Discovery

A fundamental aspect of the SM of particle physics is that the electroweak gauge interactions are spontaneously broken to electromagnetism, resulting in masses for the W and Z bosons, while the photon remains massless. The model requires that, in addition to the gauge bosons themselves, along with the quarks and leptons, new particles and interactions must also be present to account for electroweak symmetry breaking. The simplest possibility for a symmetry-breaking sector, hypothesized in the 1960s when the standard electroweak theory was developed, is to introduce a fundamental scalar field (a Higgs doublet) whose potential energy is adjusted so that it acquires a vacuum expectation value. The simplest one-doublet Higgs model makes very specific, testable, predictions. In particular, the model predicts that there will be a single neutral scalar particle (the Higgs boson) in the spectrum which couples to all massive particles – the quarks, leptons, and W and Z bosons – with definite strengths related to the masses of those particles.

A decades-long campaign in pursuit of the physics behind electroweak symmetry breaking resulted in a breakthrough in 2012, with the discovery of a new scalar particle at the LHC. The properties of this new particle are consistent with the Higgs boson of the simplest one-doublet Higgs model. In the last decade, the LHC experiments have measured many of the properties of this putative Higgs particle, including its charge, spin, CP properties, and mass, while putting stringent limits on its decay width. Existing measurements of the particle's couplings with the quarks, leptons, and electroweak gauge bosons are all consistent, within current experimental errors (typically of order $10\% - 20\%$), with the predictions of the standard Higgs models.

These experimental results indicate that the physics of electroweak symmetry breaking is, at least approximately, consistent with the simplest Higgs model hypothesized in the 1960s. However, is this minimal model the whole story? Several questions remain unanswered and we have only just begun to reveal how nature chooses to spontaneously break the electroweak symmetry. For example, we currently lack experimental knowledge of the form of the Higgs potential. This information is encoded in the couplings of the Higgs particle to gauge bosons, fermions, and itself. Implications from these investigations directly inform our understanding of the universe. For example, whether our vacuum is fundamentally stable or only metastable is tied to the Higgs potential. On the other hand, the nature of the electroweak phase transition in the early universe, which may provide the key to understanding why the universe has so much matter in it, also depends on Higgs properties and interactions.

The existence of what appears to be a fundamental scalar invites other questions. For example, how are the Higgs particle mass and electroweak symmetry breaking scale so different – by sixteen orders of magnitude – from the scales associated with gravitational phenomena? In the absence of new particles and interactions, it was expected that these two energy scales would naturally be the same. On the other hand, in the SM, the masses of the quarks and leptons arise from their couplings to the Higgs boson. Hence, the physics of the Higgs boson is associated with establishing the different "flavors" of matter which, as discussed below, is a mystery in and of itself. Information on what might lie beyond the SM is also potentially encoded in the couplings of the Higgs boson if they are measured with enough precision. For example, increased accuracy in the measurement of the SM Higgs couplings to other SM particles can be naively translated into sensitivity to heavy new physics; 10% precision is sensitive to new scales up to 1–2 TeV while a precision below the percent level would be sensitive to new physics with masses of order 10 TeV of higher. Alternatively, the Higgs boson may serve as a portal to a so-far hidden sector of new physics and be uncovered through rare "invisible" Higgs decays.

The HL-LHC will reach percent level precision on most couplings and aims at constraining the Higgs potential through a measurement of the Higgs-boson self-coupling with a projected precision of about 50%. Future colliders, both Higgs factories (mainly e^+e^- colliders with energies at the Z-pole, near the ZH threshold, and up to 1 TeV) and multi-TeV colliders (either muon or hadron colliders providing partonic center of mass energies of 10 TeV or above) are the two main avenues that will allow precision measurements of Higgs properties and interactions and, at the highest energies, potentially provide direct access to such physics. Studying the Higgs at Higgs factories, coupled with commensurate improvements in precision collider phenomenology, may uncover the scale of new BSM physics and the minimum target energy for multi-TeV machines.

1.3.2 Pursue the Physics Associated with Neutrino Mass

By the end of the twentieth century, decades-old puzzles associated with the measurements of the fluxes of neutrinos from the Sun and the atmosphere were decisively solved by a collection of gargantuan detectors of neutrinos from different sources. These revealed, rather surprisingly, that neutrino masses are tiny but definitively not zero, contradicting the assertions of the minimal version of the SM. Our understanding of nature is such that all fundamental masses are dynamical – they arise as a consequence of interactions among the massive particles and the mechanism of electroweak symmetry breaking – and we currently know nothing about the origin of nonzero neutrino masses other than the fact that new particles and interactions must exist to explain it. These new particles associated with neutrino masses can be very light or very heavy – from sub-eV to YeV (10^{24} eV) – and either charged or neutral, opening an avenue to discovery in a broad range of experiments from low-energy neutrino oscillation experiments to astrophysical neutrino detectors to high-energy colliders.

Nonzero neutrino masses were established through the discovery of neutrino oscillations, the phenomenon that describes how lepton-flavor quantum numbers are not conserved but evolve – oscillate – in space and time. The early twenty-first century has witnessed rapid experimental and theoretical progress in our understanding of neutrino oscillations. We are quickly moving from the exploratory phase to the precision era, in which oscillation experiments will be able to answer the questions of how the neutrino masses are ordered and whether neutrinos and antineutrinos oscillate differently. The mass ordering directly informs models of neutrino mass generation, and CP violation in neutrinos may play a role in the matter-antimatter asymmetry of the universe. Precise, over-constraining measurements of neutrino oscillations, which will require improved theoretical predictions of neutrino-nucleus cross sections, will test our current understanding of neutrino masses and mixings and allow us to look for more new physics in the neutrino sector. Moreover, neutrino experiments have a unique sensitivity to a wide range of weakly- or feebly-interacting new particles due to the high beam luminosity and sensitive, large detectors.

Beyond measurements of neutrino oscillations, another fundamental question we need to address is the nature of the neutrinos themselves – are they Dirac or Majorana fermions? If neutrinos have Majorana masses, that would imply that lepton number is not an exact symmetry of nature. Searches for neutrinoless double-beta decay are the most powerful probes of lepton-number violation, and an ambitious program aimed at improving existing sensitivity by at least one order of magnitude is underway. On another front, precision measurements of the kinematics of beta decay continue to probe the absolute neutrino mass scale and there are vigorous R&D efforts aiming at an order-of-magnitude improvement in sensitivity by the end of the decade. Finally, neutrinos impact the evolution of the universe and their masses leave an imprint on the large-scale structure of the universe. Cosmology-informing large-scale surveys already constrain the magnitude of the sum of neutrino masses. Future enterprises (including CMB-S4) aim at "discovering" non-zero neutrino mass by being sensitive to the minimum possible sum of neutrino masses consistent with oscillation measurements – modulo more surprises – by the end of the decade.

The degrees of freedom responsible for nonzero neutrino masses can manifest themselves in a variety of observables, many of which are not directly related to neutrinos. For example, next-generation precision measurements of charged-lepton properties (e.g., the muon $g-2$ and the electron electric-dipole moment) and the measurement of exceedingly rare charged-lepton processes (e.g., $\mu \to eee$ and $\mu \to e\gamma$ decays or $\mu \to e$-conversion in nuclei) will inform the neutrino mass puzzle; the same might also be true of precision measurements of leptonic neutral-current decays of heavy mesons. The current and next-generation of high-energy colliders are also capable of directly producing the new particles responsible for neutrino masses as long as they are neither too heavy nor too weakly coupled. Finally, cosmic surveys are not only sensitive to the values of the neutrino masses but are also impacted by new neutrino properties and interactions.

1.3.3 Identify the New Physics of Dark Matter

Precision measurements of the properties of the universe and its constituents at different distance scales – from galactic scales to clusters of galaxies, to the cosmic microwave background – combined with our understanding of gravitational interactions, indicate that most of the matter in the universe is not made SM out of particles (protons, neutrons, electrons, and neutrinos). We know very little about this so-called dark matter but there are many hypotheses regarding its nature. It can be stable or unstable and it can be a fundamental particle or a composite object. It can be very light (less than a zeV) or macroscopically heavy (dozens of solar masses). It can interact with ordinary matter a lot, a little, or only gravitationally.

Given the enormous parameter space of possibilities, a diverse experimental and theoretical effort is required in order to learn the identity and nature of dark matter and to measure its properties and interactions. If

the dark matter mass is, roughly, between 100 MeV and a TeV and it interacts with SM particles via some new "weaker-than-weak" interactions, it can be detected in very large, very quiet underground experiments. So-called WIMP searches have been pursued for a few decades and the technologies have evolved to allow for multi-ton experiments that have examined many orders of magnitude of parameter space in detail with more improvements to come. The next generation of these direct-detection searches will aim at $\mathcal{O}(10^2)$ tons of target material. These are multi-purpose experiments that are also sensitive to neutrinos from the Sun, the atmosphere, and supernova explosions. Dark matter is also expected to accumulate in the centers of galaxies and stellar objects, where it can self-annihilate or decay. These processes may lead to cosmic rays, gamma rays, neutrinos, or other cosmic messengers that can be detected on Earth (or in orbit around the Earth or the Sun) in a diverse variety of observatories. For lighter dark matter particles, new detector technologies and search strategies have opened the door to a wealth of distinct experiments. The last decade witnessed an explosion of qualitatively different searches for the QCD axion and ultra-light axion-like dark matter particles, often taking advantage of the development of new quantum devices. Meanwhile, new cosmic observational probes have been developed to study the properties of dark matter via its gravitational effects on cosmology and astrophysics.

Indirect searches for dark-matter-mediated processes in the cosmos have also evolved and diversified since the last P5, making use of the current generation of gamma-ray telescopes, X-ray telescopes, cosmic-ray detectors, and neutrino telescopes. Some of these facilities are underground, some are on the Earth's surface, and some are in orbit. Many of these detectors have upgrade programs underway, in different stages of R&D or implementation.

Alternatively, rather than searching for the dark matter present in the universe, the new particle(s) associated with the dark matter can also be produced in particle physics experiments. Experiments at high energy colliders, including the LHC, the upcoming High Luminosity LHC, and next-generation lepton and hadron colliders are well-positioned to inform the dark matter puzzle through their ability to produce and detect new particles. High-intensity experiments, including the facilities where intense neutrino beams are produced (for example, J-PARC, in Japan, or the upcoming LBNF/DUNE target and near-detector complex at FNAL), allow one to search for light new, long-lived particles that are produced in different (via weaker than SM interactions) ways and which may be observed in the near-detectors that serve the neutrino oscillation experiments. Our understanding of different ways to search for light, very weakly coupled dark matter particles has evolved dramatically in the last decade and multiple experiments sensitive to "dark sectors" have emerged and are under consideration.

1.3.4 Understand Cosmic Acceleration: Dark Energy and Inflation

Cosmic surveys allow us to measure the expansion rate of the universe as a function of time. In the 1990s, these unexpectedly revealed that today, the expansion rate of the universe is accelerating. We know very little about the fundamental physics – referred to as dark energy – responsible for this phenomenon. The simplest solution is the existence of a nonzero cosmological constant. Our current understanding of fundamental physics is essentially silent about the cosmological constant; simple estimates yield a value that is 120 orders of magnitude too large. There are also dynamical hypotheses for the origin of dark energy, associated with the existence of new fundamental fields. Learning more about the nature of dark energy is a challenge and a priority for fundamental physics in this and the upcoming decade.

Precise cosmic surveys of different cosmological eras using different tracers are needed in order to measure the expansion rate of the universe as a function of cosmological time. These include large-scale-structure measurements that will be facilitated by the Vera Rubin Observatory and next-generation measurements of

the cosmic microwave background – including its polarization. These observations are positioned to study the possible dynamical evolution of dark energy over a wide range of redshifts. On the theory side, there are several attempts to explain and interpret the physics of dark energy, which may be related to our efforts to understand quantum gravity.

There is also very compelling indirect evidence for inflation, a period of exponential expansion of the universe almost immediately after the Big Bang. The dynamics behind inflation is also virtually unknown. Measurements of the polarization patterns in the cosmic microwave background may determine the absolute energy scale of inflation, etched in the form of primordial gravitational waves, while optical spectroscopic and CMB measurements of the matter power spectrum will reveal clues about the scattering dynamics of this ultra high energy epoch as imprinted in the large scale structure of the universe. The direct observation of gravitational waves, a revolutionary discovery in 2015, has motivated studies to broaden the sensitivity and frequency reach of gravitational wave experiments. Applications to fundamental physics, including uncovering the physics of inflation along with the exploration of other early-universe phenomena (phase transitions, the imprint of ultra-heavy fields, etc.), are under intense investigation both theoretically and experimentally.

1.3.5 Explore the Unknown: New Particles, Interactions, and Physical Principles

Particle Physics research operates at the boundary between the known and the unknown. New facilities allow us to explore new distance and energy scales or unveil unexpected very rare phenomena. Broadly speaking, all particle physics experimental enterprises are sensitive to unanticipated new phenomena and have the potential to uncover new particles, new interactions, or even new principles that guide our description of fundamental physics. Exploring the unknown is at the heart of experimental and theoretical particle physics research.

The direct exploration of nature at the smallest distance scales requires high-energy collisions of fundamental particles. Very high energy collisions allow for the production of new, heavy particles, as long as these interact with the known fundamental particles. The highest laboratory center-of-mass energies are currently found at the LHC, and experiments there at the 1 TeV partonic energy scale are a central piece of particle physics research for the next decade and beyond. Access to higher center-of-mass energies in the future requires extensive R&D efforts in accelerator technologies, superconducting magnets, detector technologies, computing and data analysis, etc. Two options to reach the 10 TeV partonic energy scale have been identified: muon colliders with multi-TeV center-of-mass energies and proton colliders with one order of magnitude higher energy (around 100 TeV).

New, light particles can also be discovered in lower-energy experiments. For example, new neutral particles that mix with the electroweak neutrino partners of the SM charged leptons can be discovered via neutrino oscillations – they allow for new oscillation frequencies – and are the subject of intense experimental exploration in this decade (building on measurements made during the last few decades). Precision measurements of neutrino oscillations are also sensitive to new neutrino–matter interactions. New, light particles can also be discovered through their influence on the evolution of the Universe, as revealed by precision cosmology.

Precision measurements and the searches for rare processes are sensitive to the quantum effects of hypothetical new particles and interactions. One special class of rare-process searches involves those that are forbidden in the SM. In the SM (when neutrino masses are zero) baryon number and lepton number conservation are the consequence of accidental global symmetries. The conservation of baryon number forbids proton decay and $n \leftrightarrow \overline{n}$ oscillations while lepton-number conservation forbids neutrinoless double-beta decays. While neutrino

masses may ultimately be evidence that the lepton number is not conserved – experimental evidence is needed to prove this, as discussed above – there are no indirect or direct hints that baryon number conservation is violated. Searches for baryon-number-violating processes (which are predicted by most Grand Unified theories) serve as, sometimes, the deepest probes we have of new phenomena at very small distance scales. Very large neutrino detectors also allow the most sensitive searches for proton decay and other baryon-number-violating nuclear processes. With bigger and better-instrumented neutrino detectors our sensitivity to proton decay is expected to increase by at least one order of magnitude in the coming decade.

1.3.6 Flavor as a Tool for Discovery – Possible New Driver

At Snowmass 2021, a new Driver was proposed by the Rare Processes and Precision Measurements Frontier: *Flavor as a tool for discovery*. In the last P5, this topic was understood as included in a subset of the other science Drivers. However, new experimental capabilities and the ability for flavor probes to be sensitive to ultra-high-energy physics suggest that new physics in the flavor sector might be uncovered in the coming decade, as described below.

All matter particles come in sets of three, called generations. There are three types of charged leptons, three types of neutral leptons (neutrinos), and three different pairs of quarks whose members have charges $+2e/3$ and $-e/3$. These are postulated to have all the same properties relative to one another except for their masses, which are known to span several orders of magnitude. We don't understand this triplication of the matter particles nor is there a compelling mechanism behind the disparate masses of the different generations. In the SM, only the weak interactions allow for interactions among different generations. In the quark sector, inter-generational mixing is known to be small or very small. In the lepton sector, instead, inter-generational mixing is large or very large (albeit difficult to access in practice because neutrino masses are tiny). We don't understand how quark mixing and lepton mixing are related, if at all. Since the discovery of the muon many decades ago, the solutions to these flavor puzzles continue to elude the particle physics community.

A known consequence of the three generations, plus nontrivial mixing, is that SM interactions can account for the violation of CP invariance, a phenomenon that is well established in the quark sector. However, while the search for new CP-violating phases is still an active field of investigation in quark flavor, determining whether (and how much) CP invariance is violated in the lepton sector is an open experimental challenge for the current and next generation of neutrino oscillation experiments and among the top priorities for the LBNF/DUNE and Tokai-to-Hyper-Kamiokande projects. Understanding the physics of CP violation is a necessary ingredient for addressing another big question in fundamental physics: why is there so much more matter in the universe than antimatter? Cosmological observations and our theoretical interpretations indicate that, in the absence of new particles and interactions, the universe should be mostly empty, except for photons and neutrinos. The presence of an overabundance of matter implies a primordial matter-antimatter asymmetry. Furthermore, since the electroweak interactions are known to violate baryon number at temperatures above the electroweak phase transition, this asymmetry must be generated dynamically in the early universe, through a process known as baryogenesis. CP violation is a necessary ingredient for baryogenesis. The CP violation present in the quark sector is not sufficient to explain the matter-antimatter asymmetry in the universe. Whether the potential violation of CP invariance in the lepton sector is sufficient to account for baryogenesis is a fundamental particle physics problem that can be definitively addressed in the coming two decades.

Precision measurements of rare processes involving different generations, when complemented by precise theoretical calculations, are powerful probes of new phenomena. Searches for the virtual effects of new

particles in flavor or CP-violating observables can, in many cases, provide access to the physics at scales higher than those directly accessible at high-energy collider experiments. These include precision measurements of CP-violation in Kaon, B-meson, and D-meson mixing, and flavor-changing neutral current processes involving Kaons (e.g., $K^0 \to \pi^0\nu\overline{\nu}$), B-mesons (e.g., $B^+ \to K^+\mu^+\mu^-$), muons (e.g., $\mu \to e\gamma$), and taus (e.g., $\tau^- \to \mu^+\mu^-e^-$). These observables are the subject of active research at accelerator facilities around the world and are important targets for next-generation experiments. Some can be probed with current experiments like LHCb and the Muon $g-2$ experiment at Fermilab. Others will be investigated in the near future at Belle II. Depending on what the near future brings, dedicated next-generation experiments will be required.

At lower energies still, searches for permanent electric dipole moments of fundamental particles – electrons and muons – or baryons – protons and neutrons are also very clean probes of new particles and interactions and would reveal the existence of new sources of CP violation.

1.4 Brief Summaries of Frontier Reports

The main body of this Snowmass Report consists of the full reports of each of the ten Frontiers and the SEC report. These range from about 10 to 70 pages in length. In this section, we present a brief summary of each Frontier report, giving an overview of the material and the main high-level conclusions. For the main physics Frontiers, they discuss the large- and mid-range projects that are proposed for consideration by P5 for construction or development in the next two decades. While the brief summaries of the full Frontier reports are presented in alphabetical order, the Frontiers may be thought of as divided into two groups, "enabling frontiers" and "physics frontiers".

The enabling frontiers, namely Accelerator, Community Engagement, Computational, Instrumentation, and Underground, provide the basic foundation, infrastructure, R&D, and support on which facilities and experiments are constructed and operated and that ultimately are necessary to produce the physics. These Frontiers include experts in accelerator physics, instrumentation, and computation. These experts may be engineers, skilled technicians, computer scientists, or physicists. The line between these Frontiers and the physics frontiers is not sharp and individuals and projects may cross the boundaries. Since working scientists are the bedrock of our field, we have included the Community Engagement Frontier as an enabling technology. The Theory Frontier is both an enabling technology for HEP experiments and a highly significant physics research endeavor in its own right, producing fundamental new knowledge. For that reason, we include it among the physics frontiers.

The physics frontiers are the ones that carry out the high energy physics program, from proposal to final physics analysis and publication, and whose projects and experiments have been the main subject of P5's prioritization. These include the Cosmic, Energy, Neutrino, and Rare Processes and Precision Measurements Frontiers, and for the reasons presented above, Theory. These correspond closely to the Three Frontiers of Snowmass 2013, Energy, Cosmic, and Intensity, except that in 2021 the Intensity Frontier was split into the Neutrino Frontier and the Rare Processes and Precision Measurements Frontier to reflect the growth in the Neutrino program worldwide and in the U.S. in the last decade. These Frontiers set the physics goals and work with the enabling frontiers to ensure that the necessary infrastructure and facilities will be available to achieve them. An excellent example of this is the interaction between the Energy Frontier and the Accelerator Frontier, apparent in the two corresponding summaries in this section and further described in Section 5.

With ten Frontiers, we were concerned that communications would be difficult and stove-piping could be a problem. We implemented a very complete system of inter-frontier liaisons to ensure good interactions

among the Frontiers. At the Seattle meeting, many morning parallel sessions were dedicated to bringing together subsets of the Frontiers or their Topical Groups that benefited from interacting with each other. The work presented here is informed by the studies done by the Frontiers both individually and in collaboration.

1.4.1 Accelerator Frontier [4]

High-energy accelerators have been a major enabling technology for HEP and allied fields since the 1950s. The experiments envisioned by the Rare Process and Precision Measurement and Neutrino Frontiers rely on high-intensity proton beams to provide controlled sources of pions, kaons, neutrinos, and other particles for study. These same facilities also provide the opportunity to produce new feebly interacting particles related to the dark sector (a focus also of the Cosmic Frontier) in beam dump experiments. In contrast, the Energy Frontier requires accelerator complexes to fill storage rings of high-energy colliding beams of protons, as well as electrons and possibly muons (and their antiparticles), to allow for a thorough exploration of the properties of matter at the shortest possible distances. Despite past successes, the increasing size, cost, and timescale required for modern and future accelerator-based HEP projects arguably distinguish them as the most challenging scientific research endeavors being considered.

The goal for the Accelerator Frontier is to answer questions such as: What is needed to advance the physics? What is currently available (state of the art) around the world? What new accelerator facilities could be available in the next decade (or next-to-next decade)? What R&D would enable these future opportunities? What are the time and cost scales of the R&D and associated test facilities, as well as the time and cost scale of the final facilities?

Since the previous Snowmass/P5 exercise, the LHC Phase-1 accelerator upgrades at CERN have been completed and the planning for Phase-2 upgrades (HL-LHC) is well underway. Construction of the PIP-II proton linac for the Phase I LBNF/DUNE neutrino program at FNAL is underway, and planning for a multi-MW beam power upgrade for Phase II is beginning. In addition, numerous new high-energy colliders in various stages of maturity have been proposed. There are several e^+e^- Higgs Factory concepts, including linear colliders such as the ILC (which has a complete TDR) and others such as CLIC, C^3, and HELEN, and storage-ring proposals such as FCC-ee at CERN and CEPC in China. Finally, there is increasing interest in energy-frontier "discovery machines" with partonic center-of-mass energies of order 10 TeV, including a muon collider and a proton-proton collider, FCC-hh.

To properly support HEP scientific goals the **planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process.** The U.S. HEP accelerator R&D portfolio presently is presently managed by the general accelerator R&D program (GARD) and contains no collider-specific scope. This creates a gap in our knowledge base and accelerator/technology capabilities. It also limits our national aspiration for a leadership role in particle physics in that the U.S. cannot lead or even contribute to proposals for HEP collider facilities. To address the gap, the accelerator community proposes that the U.S. establish a **National Integrated R&D Program on future colliders** in the DOE Office of High Energy Physics (OHEP) to carry out technology R&D and accelerator design for future collider concepts. This program would aim to enable synergistic engagement in projects proposed abroad (e.g. FCC-ee/hh, ILC, and IMCC). It would also support the development of design reports on collider options by the time of the next Snowmass and P5, perhaps 7 – 10 years from now, particularly for options that can be hosted in the U.S., and the creation of R&D plans for the decades past 2030.

In addition to the collider-specific program envisioned above, general accelerator R&D is also needed. Specific needs identified include developing high-power targets for multi-MW beams for the Phase II LBNF/DUNE

upgrade and for muon collider sources; continuing development of high-gradient super-conducting and normal-conducting RF cavities for particle acceleration at linear colliders; high-field magnets for high-energy proton and muon colliders; wake-field acceleration methods to enable ultra-high energy colliders; and basic experimental, computational, and theoretical studies of accelerators and beam physics to enable the optimized design and control of future facilities. These topics require a substantial increase in accelerator R&D support, and the Accelerator Frontier recommends that the U.S. strategic goals and roadmaps of GARD program thrusts be updated.

Finally, workforce development through the strengthening of recruitment, education, and training, especially of women and other underrepresented groups, and the expansion of U.S. accelerator beam test facilities to maintain their competitiveness with respect to worldwide capabilities, are essential to realizing the vision of the Accelerator Frontier

The Accelerator Frontier of Snowmass 2021 has undertaken a thorough investigation of the current state and possible future plans that we summarize below, for which details may be found in the Frontier and Topical Group Reports (and references therein). The questions facing the frontier were addressed in seven Topical Groups led by internationally recognized researchers.

Beam Physics and Accelerator Education Funding for fundamental beam physics needs to be reinvigorated, including enhancing investment in both general and directed accelerator research. These investments should be paired with strengthening and expanding U.S. accelerator test beam capabilities. Furthermore, the U.S. accelerator physics community must comprehensively and strategically build a strong and diverse workforce of accelerator physicists to realize HEP's long-term plans.

Accelerators for Neutrinos The neutrino physics program is calling for next-generation, higher-power, megawatt and multi-MW-class super-beam facilities, such as >2MW beam power upgrade of the Fermilab proton accelerator complex. Challenges needing to be addressed include developing extremely robust targets to withstand the enormous thermal and mechanical stresses from multi-megawatt beams; major improvements to the performance and power efficiency of the linacs, synchrotrons, and accumulator rings needed for a super-beam accelerator complex; and new approaches to control instabilities and minimize beam losses.

Accelerators for Electroweak/Higgs Physics The world HEP community has called for a Higgs/Electroweak Factory as the next large accelerator project. At present, a dozen Higgs/ElectroWeak Factory proposals are under consideration, including circular e^+e^- colliders such as CEPC in China and FCC-ee at CERN and linear colliders such as CLIC (CERN) and the ILC. Two recently proposed Higgs factories can potentially be shorter than 7 km and fit the Fermilab site − C^3 and HELEN. Major conclusions of this topical group (AF3) are: of all the Higgs/EW Factory proposals considered, only a small number of them are ready or close to a construction phase − namely, the ILC, CLIC, FCC-ee, and CEPC. Most of the other proposals are in the conceptual design stage. These proposals should focus on the main R&D tasks to move forward to a CDR and, later, to a TDR. A detailed estimation of the Technical Readiness Level, risk factors, technology validation, cost reduction impact, performance achievability, and timescale are presented in detail in the Collider Implementation Task Force report [16].

Multi-TeV Colliders The Snowmass process has emphasized the emerging need to explore the Energy Frontier with particle collisions at significantly higher energies than LHC. At present only a few design concepts have achieved a level of design maturity to have reliable performance evaluations based on prior R&D and design efforts. These options reach only slightly above the 1 TeV: the linear e^+e^- collider, the ILC (1 to 3 TeV), FCC-eh (∼1.2 TeV), and CLIC (3 TeV). Critical project risks have been identified and subsystem-focused R&D is underway where necessary. Other emerging accelerator complexes offer unique opportunities to reach the very much sought 10 TeV parton energy scale, such as FCC-hh (100 TeV p-p) and a high-energy muon collider (6 – 14 TeV), which is more compact and has the potential to be more power

efficient. Both concepts still require significant basic R&D and design effort to reach a maturity level to be properly evaluated (see the Collider Implementation Task Force report [16]).

Accelerators for Physics Beyond Colliders and Rare Processes The highest priority here is the optimum exploitation of the PIP-II 800-MeV superconducting RF CW-compatible linac under construction at Fermilab. The LBNF/DUNE experiment will need only a small fraction of the total potentially available PIP-II proton beam power (bunched). The proposed RPF experiments, such as rare muon decays and dark matter searches with beam dumps, could make use of the PIP-II CW beam capability, after facility upgrades, but the bunches would have to be reconfigured to meet the varying needs of each experiment. Additionally, a new 0.8 – 1 GeV proton bunch compressor ring (PAR) has been proposed to accumulate the beam from the PIP-II linac and extract it in intense bunches at rates of 100 – 1000 Hz.

Advanced Accelerator Concepts This Topical Group focused on understanding the limits, the state of the design concepts, and the status of R&D for plasma and structure-based wakefield acceleration. At this time, there are no parameter sets for a plasma or structure-based linear collider that self-consistently address the known accelerator physics challenges. To move forward, a vigorous R&D program will be required. That should be motivated by a better understanding of the desired parameter ranges for a collider. The U.S. is in a good position in this respect with several state-of-the-art beam test facilities mainly dedicated to research in beam physics and the advanced accelerator field, including FACET-II, BELLA, ATF, AWA, and FAST-IOTA as well as at numerous universities.

Accelerator Technology - RF, Magnets, and Targets/Sources The GARD roadmap continues to serve as community-developed guidance for RF technology R&D, but based on recent progress it would benefit from some mid-course corrections detailed in the topical group report. The U.S. Magnet Development Program (U.S.-MDP) focuses on fundamental accelerator magnet R&D providing key magnet technologies that benefit all future accelerators. Discussions and initiatives emerging from Snowmass 2021 motivate enhanced scope and a significant increase in resources to prepare accelerator magnet technology for applications in future hadron and muon colliders and for fast-ramping accelerator facilities. The next generation of multi-MW high-power targets for future accelerators will use more complex geometries, novel materials, and new concepts. There are challenges in high-intensity high-brightness beam sources for future accelerators. They are particularly formidable for sources of beams with special characteristics, such as polarized electrons and ions or ultra-small emittances, and for tertiary and secondary particles, such as muons and positrons. Normal-conducting and superconducting RF technology R&D will develop toward higher gradient and higher quality factor cavities and novel, more power-efficient RF power sources.

U.S. High-Energy Physics depends crucially on the success of the Accelerator Physics Frontier, and the analyses and plans presented here provide a framework for a bright future.

1.4.2 Community Engagement Frontier [5]

In Snowmass 2013, the U.S. high-energy physics community incorporated a working group on Communication, Education, and Outreach (CE&O). The 2013 experience made clear that it is crucial to address community engagement for the health of U.S. HEP. Therefore, in Snowmass 2021 community engagement was expanded into a full-fledged Community Engagement Frontier (CEF), co-equal with the physics Frontiers and with a much broader scope than CE&O.

A major conclusion of the Community Engagement Frontier is that the climate of U.S. High-Energy Physics needs to be improved: **The HEP community should institute a broad array of practices and**

programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision.

Of particular concern is broadening the representation of the U.S. high-energy physics community. Those from marginalized communities who do join the U.S. HEP community are, all too often, subject to alienation, microaggressions, and other forms of subtle and overt discrimination. **HEP needs to address these persistent issues of underrepresentation by employing the use of robust strategic planning procedures including a full re-envisioning of our workplace norms and culture to prioritize eliminating the barriers and negative experiences faced by our marginalized colleagues.** In addressing the needs of marginalized physicists, HEP communities must engage in partnership with scholars, professionals, and other experts in several disciplines, including but not limited to anti-racism, critical race theory, and social science. Progress on these issues will require the implementation of new modes of community organization and decision-making procedures that promote agency and leadership from all stakeholders within the scientific community. In addition, all HEP communities should create structures to fully open career path opportunities to everyone and **conduct event planning to ensure events are accessible to all community members, including those with disabilities.** Finally, as demonstrated vividly during the past two years of COVID-19 lockdowns, to retain our junior colleagues, **research institutes and universities should do more to maintain the highest standard in work-life balance and mental health of staff.**

A diverse pool of candidates cannot be expected in the HEP community if educational efforts are not made as far back as the K − 12 and university undergraduate levels, to nurture the pipeline. In this regard, the HEP community should encourage stronger participation in HEP collaborations by faculty and students from non-R1 academic institutions; continue and expand work with K-12 teachers and students to create supportive local communities to nurture student interest in math and science; foster expanded pre-university and university programs for international student training, especially in partnership with colleagues in developing countries.

Engagement with developing countries needs improvement. Universities, laboratories, and HEP societies should improve and sustain international outreach, partnerships, schools, workshops, conferences, training, short visits for research, and development of research consortia; mechanisms should be developed to facilitate the participation of colleagues from developing countries. Large international research collaborations should improve efforts to facilitate the integration and participation of research groups from developing countries and support efforts to foster HEP in these countries.

Our field cannot absorb all the early career members that it produces, so **funding agencies, national laboratories and universities should work together to provide more education and career opportunities for engineering and industry-focused research within and outside HEP**, and update degree programs to match better the skills needed and career opportunities required in today's HEP and related fields. These steps should be complemented by developing effective alumni networking tools and programs, to deepen connections with industry.

Technology transfers between HEP and industry are necessary for society to receive the benefits of HEP research. Funding agencies and laboratories should improve policies and programs to foster technology transfers and facilitate collaborative programs with industry on targeted technology development beneficial for both HEP and society.

While HEP has many excellent Communication, Outreach, and Engagement programs, our community needs to enact **structural changes to foster broader, deeper, and more effective participation in community engagement**, through strengthened policies such as considering community engagement work in hiring, promotion, and grant decisions. Individual scientists should encourage others, including

peers, mentees, and students, by participating in public engagement and discussing its importance. Our community also needs to **transition from an ethos of conducting outreach and communication with the public, to a culture of engagement in relationships with the public.** This should be done by building lasting relationships with the full breadth of all our supporting communities (especially those that have been historically excluded) that are not based on transactional interactions, but rather real two-way partnerships that consider the needs and interests of the audience and include its members in program design.

The HEP community should provide resources to sustain and grow the annual HEP Congressional advocacy efforts. HEP groups should coordinate efforts by laboratories and universities to **extend advocacy to the federal executive branch, and state and local governments.** These efforts are particularly important in disseminating the results of the current Snowmass/P5 exercise. HEP should strengthen partnerships with other science and physics societies on advocacy for non-HEP funding issues.

Finally, **HEP must take greater responsibility for its impacts on climate change** by addressing and mitigating these impacts through DOE project policies and individual community member actions.

The expanded Community Engagement Frontier included seven Topical Groups defined primarily by the broad and diverse issues to be addressed, and a brief summary of their work is given below.

- **Applications and Industry:** The charge for the topical group was to develop strategies to strengthen HEP/Industry relationships. Members of this topical group produced five contributed papers examining three different modes of collaborative partnership, and cooperation on three different specific areas of technology: "Programs enabling deep technology transfer from national labs"; "Application-driven engagement with universities, synergies with other funding agencies"; "Big industry engagement to benefit HEP: microelectronics support from large CAD companies"; "Transformative technology for FLASH radiation therapy"; and "Nurturing the industrial accelerator technology base in the U.S.".

- **Career Pipeline and Development:** This working group was not simply about making early career scientists aware of different opportunities, but also about changing the culture of HEP career paths. Two topics were studied, namely: "Facilitating Non-HEP Career Transition" and "Enhancing HEP research in predominantly undergraduate institutions and community colleges".

- **Diversity, Equity, and Inclusion:** The DEI topical group focused on issues and projects related to Diversity, Inclusion, Equity, and Accessibility; all of which are essential not only to professional success in our field but to develope a better society at large. Ultimately, twelve contributed papers were developed, which may be categorized as follows: "Accessibility in High Energy Physics: Lessons from the Snowmass"; "Lifestyle and personal wellness in particle physics research"; "Climate of the Field: Snowmass 2021"; "Why should the United States care about high energy physics in Africa and Latin America"; "Experiences of Marginalized Communities in HEP"; "In Search of Excellence and Equity in Physics"; and "Strategies in Education, Outreach, and Inclusion to Enhance the U.S. Workforce in Accelerator Science and Engineering".

- **Physics Education:** The Physics Education topical group, examined the role that physics education at all levels plays in advancing the field of HEP. Two goals were identified as critical for the long-term health of the field: attracting students across all demographics to the study of physics, and providing them the education, training, and skills they will need to pursue any career in STEM or related fields. The working group contributed papers are: "Opportunities for Particle Physics Engagement in K-12 Schools and Undergraduate Education"; "Transforming U.S. Particle Physics Education: A Snowmass 2021 Study"; "Broadening the Scope of Education, Career and Open Science in HEP"; "The Necessity of International Particle Physics Opportunities for American Education"; "Data Science and Machine

Learning in Education"; and "U.S. CMS - PURSUE (Program for Undergraduate Research Summer Experience)".

- **Public Education and Outreach:** The Public Education and Outreach working group focused on enabling members of the physics community to effectively communicate about scientific research through public engagement. The contributions to this working group resulted in two contributed paper topics, namely, "The need for structural changes to create impactful public engagement in U.S. particle physics" and "Particle Physics Outreach at Non-traditional Venues".
- **Public Policy and Government Engagement:** The topical group on Public Policy and Government Engagement was tasked with conducting a review of all current interactions between the HEP community and government offices and individuals. Three contributed papers produced by the topical group document this work: "Congressional Advocacy for HEP Funding"; "Congressional Advocacy for Areas Beyond HEP Funding"; and "Non-congressional Government Engagement".
- **Environmental and Societal Impacts:** This topical group focused on ideas and projects related to how particle physics research impacts society and the environment. Five contributed papers were developed and submitted to this group, focusing on three areas: environmental impacts of particle physics; interactions of different laboratories with their local communities; and nuclear non-proliferation.

The recommendations made by CEF are to improve and sustain strategic engagements with our communities in order to draw support for and strengthen the field of particle physics (an inward-focused goal carried forward from Snowmass 2013) while playing key roles in serving those communities (an outward-focused goal added for Snowmass 2021). **It is critical that we as individuals agree on the importance of all working together to address CEF issues in HEP. DPF should work in collaboration with all HEP stakeholders to develop a structure for implementing the recommendations contained in the CEF report.**

1.4.3 Computational Frontier [6]

Software and computing (S&C) is essential to all high-energy physics experiments, accelerator and detector design, and many theoretical studies. It is a key enabler of all the other Frontiers and all science Drivers, requiring physics research along with expertise in computer science to address the complex and unique challenges of our field. The escalating demand for computing resources is a result of the need to do more sensitive and more precise experiments, using higher intensity beams, higher luminosity colliders, and stronger sources, to collect more astrophysical data over wider fields and farther into the past (higher red-shifts), and to do more precise theoretical calculations. While experiments may last for many decades and their experimental hardware may be upgraded a few times during this period, the computing hardware they use, driven by the commercial sector, may change every half-decade or even more frequently. The software for the detectors and facilities evolves continuously to respond to operational issues, but undergoes larger changes to respond to major detector upgrades, and must also adapt on shorter time scales to utilize and exploit the latest computing hardware and software and computing infrastructure changes. In the last decade, limited computing resources have gone much farther than expected due to methodological innovation, but it is highly likely that analyzing all the data to be acquired in the next decades will stress the community's financial and human resources. While we cannot predict with any accuracy what the specific S&C environment will look like in 2035 or 2045, we can try to create an R&D environment for computing hardware and software that will allow HEP to adapt to whatever changes occur so it can utilize the most cost-effective methods.

S&C had a prominent role in the 2013 Snowmass report. However, in the ten years since then, many new features and trends appeared that were absent or hardly noticeable then. These include

- The use of heterogeneous accelerators such as GPUs and FPGAs, off-loading parts of calculations. These devices come from the commercial sector, with significant implications for the way we develop and maintain software. Computing has entered a new "post-Moore's law" phase. Speeds-ups in processing now come from the use of parallelism within computations rather than higher clock speeds. This paradigm shift has brought up the enormous challenge of adapting or re-engineering almost every piece of HEP software, a process that is heavy in labor and requires rare and expensive expertise.
- The reliance on community hardware resources such as High-Performance Computing (HPC) centers and the Cloud rather than dedicated experiment resources to do production and very compute-intensive application. HPC facilities are not specifically designed for HEP experiments, thus using them effectively requires significant investment in R&D to address technical challenges related to task factorization, I/O, storage, and utilization of external services.
- The pervasive use of artificial intelligence and machine learning, AI/ML, in nearly every aspect of our software. Hardly mentioned in the 2013 report, these revolutionary machine-learning approaches are transforming the way we work.
- The appearance of potentially disruptive technologies, such as quantum computing. These are R&D projects, and we still need to understand which, if any, HEP computing needs they satisfy.

It continues to be true today, as it was in 2013, that S&C efforts are neither funded nor managed like projects in the manner that major facilities and experiments are. They are funded by various streams including dedicated resources for large experiments, shared resource pools provided for general use by small and large groups, and national computing centers provided by national funding agencies for large, multidisciplinary projects and communities. Increasingly, HEP researchers are being encouraged to use these computing centers, as well as commercial resources available in the Cloud.

This new computing environment requires R&D and novel approaches to address the long-term development, maintenance, and user support of essential software packages and cross-cutting R&D efforts supported from proof of concept to prototyping and production. Additionally, strong investment in career development for software and computing researchers is needed to ensure future success. All of our computing tasks in HEP are likely to be affected by these changes, so common solutions across HEP, other sciences, government, and industry are going to be necessary.

The high-level conclusions of the Computational Frontier are:

- **The creation of a standing "Coordinating Panel for Software and Computing"** under the auspices of the APS Division of Particles and Fields, mirroring the Coordinating Panel for Advanced Detectors (CPAD) established in 2012. As with CPAD, this would, among other things, require a modification of the DPF bylaws. A suggested mandate is:
  Purpose: Promote, coordinate, and assist the HEP community on Software and Computing, working with scientific collaborations, grassroots organizations, institutes and centers, community leaders, and funding agencies on the evolving HEP Software and Computing needs of experimental, observational, and theoretical aspects of the HEP programs. The scope should include research, development, maintenance, and user support.
- **Support of software packages** The U.S. HEP Community should take a leading role in the long-term development, maintenance, and user support of essential software packages with targeted investment.

Support of software for HEP has been uncertain in the U.S. An excellent example is GEANT4, which does not receive dedicated support in the U.S. at present and yet is critical to most HEP programs, where it is used in facilities prospect studies, detector design and optimization, computing infrastructure stress tests, software development, and physics analysis. Event generators are another example.

- **Support for R&D** Through existing, reshaped, and expanded programs, R&D efforts cutting across project or discipline boundaries should be supported from proof of concept to prototype to production.
- **Support for necessary personnel to enable the use of heterogeneous resources** Support for computing professionals/researchers and physicists to conduct code re-engineering and adaptation will enable the most effective use of heterogeneous resources.
- **Training, career development, and EDI** Strong investment in career development for HEP S&C researchers will ensure future success.

These recommendations of the Snowmass Computational Frontier resonate with the European Strategy, spelled out in their recent report [17].

In 2013, Computing was organized along frontier lines. In Snowmass 2021, Computing instead organized itself in Topical Groups that are all cross-cutting in nature to reflect the need for common solutions to computing challenges. The seven Topical Groups are Experimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and Processing Resource Access, End User Analysis, Quantum Computing, and Reinterpretation and Long-term Preservation of Data and Code. The following is a summary of important observations and conclusions from each of the seven Topical Groups of the Computational Frontier.

Experimental Algorithm Parallelization This topical Group covers event and physics object reconstruction for all experiments and comparable work for surveys. Workable and portable solutions must be found and supported to exploit heterogeneous computing platforms. In parallel, targeted optimizations of key algorithms for experiments, which often provide the largest speedups, must also be developed and supported. Software frameworks and common tools must evolve and adapt to the new computing landscape to enable the usage of parallel algorithms in production environments of big and small experiments. Interdisciplinary collaborations and programs will play a critical role. Training opportunities for early-career researchers are essential, and career opportunities for researchers who focus on algorithm development need to be created. To enable the long-term sustainability of HEP software and provide job security to researchers in this area, software development should be supported according to a model similar to that for detector projects, or as part of detector projects. Funding should continue beyond the R&D phase of algorithm exploration and extend into the development, production, and maintenance phases. Funding agencies and research teams have to commit to sustainable long-term effort for mission-critical software products: big experiments/surveys need multi-year, rather than annual, computing resource allocation planning for the use of national facilities.

Theoretical Calculations and Simulation Simulations and theory calculations are used in nearly all aspects of HEP. For this study, the topic was divided into six domains: cosmic calculations, particle accelerator modeling, detector simulation, event generators, perturbative calculations, and lattice quantum chromodynamics (QCD). Each area has specific needs, but there is also significant commonality, leading to the following general conclusions. Hardware accelerator-friendly portable common tools are essential. Universal programming interfaces should be developed to facilitate portability. CPU clusters will still be necessary to provide general-purpose computational cycles for tasks that do not map well to accelerators but these must be carefully sized to the actual needs. Automation of memory hierarchy will remove a burden from the scientific programmer and enhance productivity. Best practices for the development of common

software should be encouraged. Working with funding agencies, new arrangements should be established for long-term support and maintenance of common software tools. Collaboration of computer scientists, applied mathematicians, nuclear physicists, and others relevant to HEP computational and physics model development should be encouraged and supported. Programs should be developed, including joint lab-university tenure-track appointments in S&C, to generate academic opportunities for young researchers in computation in academia. Training for graduate students and postdocs in AI/ML should be provided.

Machine Learning Machine Learning ML/AI techniques are firmly embedded in HEP and their use is still growing. Areas where dedicated resources are required for ML to continue to expand and flourish include:

- **Dedicated HEP-ML Research** While industry is driving research in ML, there are specific areas where its use in HEP requires dedicated solutions, such as in uncertainty quantification, validation, and interpretability. Ideas such as anomaly detection and simulation-based inference may enable analyses that are not currently possible. ML may also be of use in the design, quality assurance, and control and calibration of instrumentation and in control at accelerator facilities and experiments, especially where ultra-low latency is required for correction. Much of this work is inherently interdisciplinary.
- **Software and hardware needs** HEP now relies on industry standards such as TensorFlow, SciPy, and PyTorch. There is also a diverse set of hardware that supports ML, most involving GPUs, which are mainly available at computing centers. Small hardware setups available through research grants would help stimulate research. At the same time, industry continues to develop more advanced hardware accelerators whose development the HEP community should track and participate in so that its needs can be met. The HEP community should be trained in the use of demand services as a way to access the latest custom hardware.
- **Training and Personnel** ML/AI should be part of the standard training program. Courses should be available in graduate school and in summer schools. Training materials and paths should be readily available. Many of the issues connected to the use of ML are statistical in nature so researchers need formal training in that as well. It is also important that career paths be available to researchers with these broad and cross-cutting capabilities.

Storage and Processing Resource Access This group concentrated on the R&D challenges that must be addressed in the next decade so that HEP can take advantage of the newest developments, which will most likely come from industry. It did not focus on the required capacity for computing or storage. The complex HEP workflow is divided into six areas – storage, processing, edge services, AI/ML hardware, analysis facilities, and networking. Each of these is examined in detail in the report and four overarching themes have emerged: efficiently exploit specialized compute architectures and systems; invest in portable and reproducible software and computing solutions to allow exploitation of diverse facilities; embrace disaggregation of systems and facilities; and extend common interfaces to diverse facilities. HPC facilities, often several different ones, will be needed to do major processing workflows for the analysis of experiments. There are four recommendations for work that will facilitate the use of these diverse capabilities for processing HEP data: HPC facilities should revisit their resource access policies to allow more flexible allocations and job executions so that more HEP projects can benefit from the large computing facilities; investment in the development of portable software is key to maximizing the efficient utilization of diverse processing resources; research is needed to determine the trade-off between dedicated HEP computing facilities and general access computing facilities such as the HPC center, Grid and Cloud resources; and infrastructure development will be needed to support better data management frameworks across different types of facilities.

End User Analysis Two analysis ecosystems are used in HEP, one based on ROOT, hosted by CERN, with U.S. support, especially in the area of I/O, and the other based on Python, which is a set of analysis tools

developed primarily to host analysis software, including ML/AI, developed outside of HEP. One challenge is that increasingly running on massive amounts of data will be done at HPCs. Particle physics analysis problems usually require relatively light-weight computations to be done repeatedly on massive numbers of events, often referred to as high-throughput computing (HTC). High-Performance Computing center execution environments are usually not needed for HEP analysis and may introduce constraints and overheads that make it difficult to use them efficiently. Actions that need to be taken to serve the needs of the HEP community for long-term, sustainable end-user analysis are identified:

- Develop both ROOT-based and Python-based analysis ecosystems and maintain interoperability between them.
- Critical elements of the ROOT evolution plans include the development of improved columnar data formats and multiple I/O implementations.
- Analysis facilities for low latency columnar analysis in the context of the Python ecosystem will be essential for future experiments.

User-friendly data provenance and metadata storage systems that can be easily integrated into typical analysis tasks should be developed. Scaleable analysis models should be developed so users can perform small interactive tests and also can run over large datasets using a single interface. Pipelines compatible with long-term preservation should be built into the structure of analysis systems. Collaborative software is an important element of the analysis software stack of an experiment and includes documentation, messaging between users, discussion forums, software version control, bug tracking, and document workflow management. Host laboratories should provide a full stack of these services to their experiments, large and small. Documentation and training must be produced for analysis software understood as an ecosystem, not as a disconnected set of packages.

Quantum Computing Quantum computing is an exciting new technology that can be shown to outperform classical computers in certain applications. However, current quantum computers (QCs) are relatively small and suffer from vulnerability to noise. This Topical Group focused solely on the use of re-programmable quantum hardware. It is not clear where it will be advantageous to employ QC in HEP, but there are a number of benchmark problems where QC is expected to be useful and perhaps even transformational, including lattice QCD, event generation, and data analysis. Currently, there is no consensus on the best hardware for implementing quantum computers and there are several software packages available. Access to QC hardware is also a problem. Nevertheless, we should support research by HEP physicists, in collaboration with industry and academia, to explore this rapidly developing field which may eventually offer substantial benefits to HEP. The National QIS Research Centers are a significant step in this direction.

Reinterpretation and Long-term Preservation of Data and Code This group considered how data, simulations, analyses, and codes needed to do an analysis can be preserved so that the analysis could, for example, be repeated well after the experiment that took the data ended. The purpose might be to verify the original analysis, try to improve it using new methods or concepts, use the data for some new analysis, or combine it with some other analysis. Recommendations in this area include:

- Ensuring that all running and in-preparation experiments have a strategy and resources for the long-term preservation of data and analysis capabilities.
- Investing in shared cyber-infrastructure to preserve these data and support a comprehensive analysis from various experiments and surveys – both active and completed – in order to realize their full scientific impact. The infrastructure should support the requisite theoretical inputs and computational

requirements for analysis as well as metadata and APIs to track provenance and provide incentives for participation.

- As a specific example, there should be a data archive center to preserve Cosmic Frontier datasets and simulations, and facilitate their joint analysis across different computing centers. Preservation needs are not restricted to experimental data and analyses. As an example, for many years, the lattice QCD community has had a tradition of sharing the expensive-to-produce gauge configurations that can be used for many physics analyses.

Software and computing technologies traverse all areas of HEP and are evolving rapidly. It is hard to imagine what the state of the art will be at the time of the next Snowmass in about a decade. It is our hope that the establishment of a Coordinating Panel for Software and Computing will serve the community on timescales commensurate with the rapid evolution of S&C technologies.

1.4.4 Cosmic Frontier [7]

The Cosmic Frontier is focused on understanding how elementary particle physics shapes the behavior and evolution of the universe, and how observations of the universe inform our understanding of physics beyond the SM. In the moments just after the Big Bang, fundamental physics governs the production of the particles and energy fluctuations that give rise to the current universe. The properties of elementary particles also govern the behavior of the most energetic processes observed in the universe today, including supernovas. The physics questions which guide the cosmic frontier include:

- **What is the nature of dark matter?**

  Does dark matter interact with ordinary matter, perhaps via the Higgs boson or another mediator? Is dark matter bosonic and does it exhibit wave-like properties? Does the dark sector itself have non-trivial dynamics, and does dark matter interact with itself? How was dark matter produced in the early universe? Does the nature of dark matter have general implications for physics beyond the SM?

- **What is the nature of dark energy?**

  Is the observed acceleration in the expansion rate of the universe due to a new energy component or does it require modifications to general relativity? If dark energy is a new energy density component, is it a cosmological constant or is it a dynamical quantity changing in time? When did dark energy become important in the history of the universe?

- **How is the inflationary paradigm realized in nature?**

  What is the energy scale of primordial inflation? Does inflation have dynamics that manifest themselves as an observable imprint on the primordial distribution of matter fluctuations? Detect or place limits on "B-modes" to discriminate among theories of the Big Bang. Why were there two eras of acceleration in the history of the universe, one early and one late?

- **How can we use cosmic observations to learn about BSM physics?**

  Did BSM degrees of freedom influence the thermal history of the universe? What is the scale of neutrino masses? Can cosmological observations distinguish between the ordinary and inverted neutrino mass hierarchies? What do gravitational waves reveal about early Universe dynamics and phase transitions? What do Nature's highest energy particles produced in cosmic sources tell us about BSM particles and interactions?

A major thrust of the future Cosmic Frontier program is building the next generation of cosmological probes. Cosmic surveys "aim high" at observables spanning almost the entire 13.8 billion-year history of our Universe. The next big project in this arena is CMB-S4, a system of telescopes to study the cosmic microwave background and address the mystery of cosmic inflation, which is expected to operate through to at least 2036. Additional projects that would start after 2029 are Spec-S5 (the follow-on spectroscopic device to DESI), a project to carry out line intensity mapping (LIM), and planning efforts to increase the sensitivity of gravity wave detection by at least a factor of 10 (10^3 in sensitive volume) beyond what will be achieved by LIGO/Virgo.

In the Cosmic Frontier survey ecosystem, each type of program brings unique strengths to the portfolio, including shape measurements that can only come from imaging, precise and robust redshift measurements that require spectroscopy, and multi-messenger data that exploits new gravitational wave detection capabilities; by also spanning a range in wavelength (e.g., Optical/IR vs. mm-wave vs. 21-cm), information from different redshift ranges can be accessed. While each survey will deliver groundbreaking results on its own, no single experiment can meet all of the discovery thresholds without complementary information from other programs.

A second thrust of the Cosmic Frontier is a suite of experiments to explore the physics of dark matter (DM). The space of DM models encompasses a dizzying array of possibilities representing many orders of magnitude in mass and couplings, making the DM program one of the most "interdisciplinary" investigations in high-energy and particle physics. The Cosmic Frontier's DM program will "delve deep, search wide" by employing a broad portfolio of small/medium-scale direct and indirect detection experiments, as is required to search optimally for each decade in dark matter mass. Furthermore, an expanded Cosmic Probes program will strive to identify the properties of dark matter via cosmic surveys, which is highly synergistic with the other science targeted by those surveys.

The DM research program enhances adjacent areas of science. New DM detector technologies will require cross-disciplinary collaborations to access the expertise, technology, and facilities of neighboring fields of study such as AMO, condensed matter physics, quantum information science, and gravitational physics. Similar synergy between fields is present when searching for indirect effects of dark matter scattering, annihilation, or decay in galactic halos, where HEP provides a critical role in developing instrumentation for astroparticle observatories. Equally important, collaboration with the broader non-HEP astronomy and astrophysics community is essential for understanding the astrophysical backgrounds in DM searches, while at the same time alerting those communities to possible non-gravitational DM impacts.

The conclusions of this Frontier arise from the work of the seven Topical Groups of this Frontier, which were organized into three general categories as described below.

Dark Matter

Our understanding of the landscape of dark matter theories has evolved significantly in the past several years, as theoretical exploration has better defined the boundaries of what models are consistent with observations. As of Snowmass 2013, the classification of dark matter candidates was largely based on the particle physics features of the underlying models. Since then, the focus has shifted toward exploring a wide range of possible phenomena in an effort to understand how well existing experimental searches cover the space of possibilities, and how new experimental opportunities provide sensitivity to regions of theory space that are not captured by the current program.

- **Particle-like Dark Matter:** In conventional models of GeV-TeV mass dark matter associated with solving the electroweak gauge hierarchy problem, WIMPs with electroweak couplings to SM particles

would be naturally populated at approximately the correct density by the freeze-out mechanism. Large second-generation WIMP detectors based on a variety of scattering targets, combined with indirect searches for high-energy annihilation products, have excluded Z-mediated couplings to SM particles for WIMP masses up to ∼TeV. Experiments are now probing weaker couplings such as those mediated by Higgs boson exchange and exploring new techniques to be sensitive to light particle dark matter (1 eV to 1 GeV).

- **Wave-like Dark Matter:** Provided that gravitational clumping of a single dark matter species is responsible for the formation of all galaxies and galactic substructures, the sizes of the dark matter halos provide a quantum-mechanical lower bound on the mass of dark matter of order 10^{-22} eV. For dark matter mass less than 100 eV, the mode occupation number must exceed unity in order for there to be enough dark matter to account for the local gravitational well. Hence dark matter in the mass range from 10^{-22} eV to 10^2 eV must be wave-like bosonic fields. A high-priority target in this mass range is the QCD axion, and perhaps the most significant technological development in the field of terrestrial dark matter searches since the last Snowmass is the demonstration by ADMX and HAYSTAC of experimental sensitivity to the invisible QCD axion made possible through the use of quantum sensing technologies. A comprehensive search for the QCD axion is now within reach, but this program will require significant investment in high-field magnets which serve as the axion scattering target.

- **Cosmic Probes of Dark Matter:** Cosmic probes of dark matter, which seek to determine the fundamental properties of dark matter through observations of the cosmos, have emerged as a promising means to reveal the nature of dark matter, and are valid even when the coupling between dark matter and normal matter is extremely weak (e.g., as weak as gravity). Rubin LSST has enormous potential to discover new physics beyond the prevailing cold dark matter paradigm. Microlensing measurements will directly probe primordial black holes as a component of dark matter. The planned CMB-S4 and future Spec-S5 and CMB-S5 projects will also extend access to rich dark matter particle physics. These probes also constrain neutrino physics. The current cosmological limit on the sum of the neutrino masses is $\sum m_\nu < 0.12$ eV as obtained using cosmic microwave background, baryon acoustic oscillations, supernova Ia, and large-scale structure measurements. CMB-S4 will reach sensitivity $\sum m_\nu < 0.02$ eV, and if the data indicate a mass sum less than 0.11 eV, this would rule out the inverted neutrino mass ordering which predicts a higher mass sum.

Dark Energy and Cosmic Inflation

Developing an understanding of the cause of cosmic acceleration in the modern universe would revolutionize our understanding of fundamental physics. Cosmology research in the twenty-first century is dominated by large cosmic survey experiments carried out by worldwide collaborations comprising hundreds of members from dozens of institutions. The goal is to study both early and late universe phase transitions and the new particles and interaction dynamics governing new fundamental scales of nature. New measurements will establish the values of key parameters, including the equation of state parameter of dark energy, the rate of expansion of the universe today, and the amplitudes of fluctuations in the density of matter in the universe.

- **The Modern Universe:** The community's input to this Topical Group jointly describes a multi-probe experimental program that provides a rich, deep, and flexible portfolio that provides powerful constraints on cosmic acceleration. The program includes a powerful new Stage V spectroscopic facility (also referred to here as Spec-S5) that would pursue larger and deeper surveys enabling transformational advances in our understanding of both eras of accelerated expansion in the history of the universe – the early inflationary epoch and the late dark energy-driven one.

- **Cosmic Dawn and Before:** The scientific goals of this Topical Group are to study inflation and to search for new physics through precision measurements of the Cosmic Microwave Background (CMB) from the early universe. Polarization-sensitive experiments like CMB-S4 offer unique windows on the B-mode patterns, which reveal the absolute energy scale of inflation and will continue to provide precision measurements of the other key observables. Upcoming cosmic surveys including DESI and the envisioned Spec-S5 project will provide much larger datasets, using precise redshift determinations to map the matter distribution in all 3 dimensions instead of being constrained to a single 2-dimensional slice at the surface of the last scattering. A new technique of line intensity mapping (LIM) of the 3-d distributions of neutral hydrogen or other gas will possibly access the largest range of redshifts to provide the highest statistics measurements of the large-scale structure.
- **Complementarity of Probes and New Facilities:** This topical group presented a multi-faceted vision for the cosmic survey program which provided a path to understanding the causes of early- and late-time acceleration by leveraging ongoing surveys, developing and demonstrating new technologies, and constructing and operating new instruments The previously mentioned large CMB-S4 project and the next large Stage V Spectroscopic Facility (Spec-S5) should play a key role in advances over the next decade and beyond. The vision also includes potential future surveys that will be enabled by near-term R&D and small pathfinder initiatives; these projects would employ new technologies and techniques such as 21-cm and mm-wave Line Intensity Mapping (LIM), Gravitational Wave Observatories (GWO), and future broadband CMB imaging (CMB-S5).

Cosmic Probes of Fundamental Physics

Cosmic Probes of Fundamental Physics encompass a multitude of approaches:

- **Very high energy particles (ultra-high energy cosmic rays, gamma rays, and neutrinos):** The discovery of TeV−PeV astrophysical neutrinos opens up unique opportunities to probe the neutrino sector at energy scales not accessible with laboratory neutrino beams; high-energy neutrinos from IceCube were used to discover the Glashow resonance and measure the high-energy neutrino-nucleon cross section and inelasticity distribution. UHECR air showers probe hadronic interactions at center-of-mass energies an order of magnitude beyond the LHC; they have been used to determine the p-p cross section and have established significant failings in state-of-the-art modeling of hadronic interactions. Upper limits on UHE gammas and neutrinos constrain GUT-scale physics.
- **Gravitational waves and neutron star observations:** The LIGO-Virgo collaboration has observed many examples of binary black holes, BH-neutron stars, and binary NS mergers, revealing an unexpected population of black holes with masses up to several hundred $M_{\odot}$. LV and NICER have measured the radii of neutron stars, forcing a re-evaluation of the QCD equation of state at very high density. Future measurements with a next-generation gravitational wave observatory, will nail down crucial aspects of QCD and probe some scenarios of inflation and phase transitions in the early universe.
- **Multi-messenger astrophysics:** The dawn of a new astrophysical multi-messenger era has been heralded by the recent co-detection of gamma rays and gravitational waves in a binary neutron star merger, the co-detection of gamma rays and neutrinos in a blazar flare, and several examples of neutrinos consistent with production in tidal disruption events. Over the next decade, simultaneous observations with different techniques promise to reveal where these extreme-energy cosmic messengers come from, and how they came to be.

To summarize, the Cosmic Frontier strategy detailed in this report encompasses a science-rich program with small, medium, and large experiments which are planned on both near-term and long-term timescales. The

community consensus is that this coming decade must feature strong support for this program in full to ensure that HEP will enjoy the new era of discovery and groundbreaking precision measurements that have been promised for the next two decades, as well as building even more powerful experiments to reach key science thresholds.

1.4.5 Energy Frontier [8]

After decades of pioneering explorations and milestone discoveries, the SM of particle physics has been confirmed as the theory that describes electroweak and strong interactions up to energies of a few hundred GeV with great accuracy. However, the SM also leaves several fundamental questions unexplained such as the details of the evolution of the early universe, the origin of the matter-antimatter asymmetry of the universe, the nature of dark matter, the origin of neutrino masses, the origin of the electroweak scale, and the origin of flavor dynamics. The answers to these questions must lie in BSM physics.

In this context, colliders at the energy frontier offer the unique opportunity to study a huge number of phenomena and explore the connection between many of the fundamental questions we want to answer. The Energy Frontier (EF) aims at advancing the investigation of such questions with a broad and strongly motivated physics program that will push the exploration of particle physics to the TeV energy scale and beyond. The sharply focused EF agenda includes in-depth studies of the SM as well as the exploration of physics beyond the SM to discover new particles and interactions. The EF vision keeps its focus on big questions and provides opportunities to examine them from as many angles as possible while also continuing to pursue the exploration of the unknown, a leading driver of the EF physics program.

The EF currently has a top-notch program with the LHC and the HL-LHC at CERN, which sets the basis for the EF vision. The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no obvious and unambiguous signal of BSM physics. This implies that either there is a gap in the scale of new physics, or BSM physics must be weakly coupled to the SM or hidden in backgrounds at the LHC. The HL-LHC will either strengthen these conclusions further or point us in a particular direction for discovery. At the same time, the discovery of the Higgs boson at the LHC has provided us with the unique possibility of exploring the most mysterious aspects of electroweak interactions because of a thorough program of Higgs-boson precision physics that has been very successfully started by the LHC. The studies of the Higgs-boson properties will reach a new level of precision at the HL-LHC and have the potential to indirectly probe new physics in the 10-TeV range and beyond, due to the higher precision and energy reaches of future lepton and hadron colliders. Auxiliary forward-physics facilities will further extend the physics potential of the HL-LHC both for SM measurements and BSM discoveries. In view of all these considerations, **the EF supports continued strong U.S. participation in the success of the LHC, and the HL-LHC construction, operations, and physics programs, including auxiliary experiments.**

Colliders are the ultimate tool to carry out the EF program thanks to the broad and complementary set of measurements and searches they enable. With a combined strategy of precision measurements and high-energy exploration, future lepton colliders starting at energies as low as a few hundred GeV up to a few TeV can shed substantial light on some of these key questions. Ultimately, it will be crucial to find a way to carry out experiments at higher energy scales, directly probing new physics at the 10 TeV energy scale and beyond. The EF community has proposed several opportunities for pursuing its scientific goals, among them the most prominent ones are **Higgs-boson factories** and **multi-TeV colliders** at the energy frontier. These projects have the potential to be truly transformative as they will push the boundaries of our knowledge by testing the limits of the SM and directly discovering new physics beyond the SM. Thus, **the**

EF affirms that it is essential to complete the HL-LHC program, to support the construction of a Higgs-boson Factory, and to ensure the long-term viability of the field by developing a multi-TeV energy-frontier facility such as a muon collider or a hadron collider.

The discussions on projects that extend the reach of the HL-LHC underlined that preparations for the next collider experiments have to start now to maintain and strengthen the vitality and motivation of the community. Several projects have been proposed such as ILC, CLIC, FCC-ee, CEPC, C^3, or HELEN for e^+e^- Higgs factories, and CLIC at 3 TeV center-of-mass energy, FCC-hh, SPPC and Muon Collider for multi-TeV colliders. **The EF supports a fast start for construction of an e^+e^- Higgs Factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs Factory will require an immediate, vigorous, and targeted Detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.**

The EF aims to facilitate U.S. leadership in an innovative, comprehensive, and international program of collider physics. The timescales to fully realize the EF vision extend to the end of this century, and the ultimate goals can only be realized if our actions foster a vibrant, diverse, and intellectually rich U.S. EF community. Maintaining and strengthening such a community is only possible if our plans reflect the aspirations of and provide a rich set of opportunities for our Early Career physicists. **The U.S. EF community has also expressed renewed interest and ambition to bring back EF collider physics to U.S. soil, maintaining its international collaborative partnerships and obligations.**

The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

These conclusions were derived from the analyses of the ten Topical Groups in the Energy Frontier, which were divided into three major areas broadly defined as Electroweak Physics (Higgs-boson physics, top-quark and heavy-flavor physics, electroweak gauge bosons physics), Strong Interactions (precision QCD, hadronic structure and forward QCD, heavy ions), and BSM (model-specific explorations, general explorations, dark matter at colliders), which have focused on three main key questions:

- **What can we learn about the origin of the electroweak scale and the electroweak phase transition from an in-depth study of the SM?**
- **What can we learn about the nature of strong interactions in different regimes?**
- **How is a complete program of BSM searches built that includes both model-specific and model-independent explorations?**

A summary of the outcomes from the ten Topical Groups is included below.

Electroweak Physics

- **Higgs Boson Properties and Couplings:** The Higgs boson is central to the electroweak sector of the SM and, in the ten years since the discovery of the Higgs boson, measurements of its mass are now at the per-mille level and several couplings are now measured at the $5\% - 10\%$ level. The precision measurement of the Higgs boson properties is the central component of the physics of Higgs factories, with a goal of reaching coupling accuracies at or below the percent level. Of particular importance in the future is the measurement of the Higgs triple-coupling, a direct measure of the dynamics associated with electroweak symmetry-breaking, and which (for SM the prediction, in which this self-coupling is directly related to the Higgs mass) should be measured at the 50% level at the HL-LHC, and the $10\% - 20\%$ level at high-energy e^+e^- colliders. Precision measurements (at the few percent levels) of the Higgs self-coupling, however, require colliders with partonic center-of-mass energies of order 10 TeV, such as the FCC-hh or a muon collider.
- **The Higgs Boson as a Portal to New Physics:** The scalar sector of the SM could be extended in many ways, such as through the addition of a scalar singlet (real or complex) or through one or more electroweak doublets as in Two Higgs Doublet Models (2HDMs). The phenomenology of these and related models are rich and complex, and new colliders can extend limits on these models beyond what is possible at the HL-LHC through either precision measurements of Higgs and electroweak couplings or via direct production of new heavy scalar states. For example, new techniques for strange-quark tagging at the ILC could allow measurements to directly probe the Higgs coupling to the second generation, providing a window into flavor physics.
- **Heavy Flavor and Top Quark Physics:** The top quark is the heaviest SM particle and is therefore the quark that couples most strongly to the electroweak symmetry-breaking sector. Accurate measurements of the top-quark mass, production cross sections, and couplings at future colliders provide incisive tests of the SM and probes for new physics. For example, the ultimate precision in the top-quark mass can be reached in a scan of the top-quark production threshold at a future lepton collider, where uncertainties on the top-quark mass are estimated to fall to 40 MeV$-$75 MeV $-$ approximately an order of magnitude lower than achievable today.
- **Electroweak Precision Physics and Constraining New Physics:** Precision measurements of electroweak observables have and will continue to provide stringent tests of the SM and windows into physics beyond the SM. While the HL-LHC will provide accurate measurements of the W-boson mass,

the top-quark mass, and the effective weak mixing angle through Drell-Yan production, future high-intensity e^+e^- running at the Z-pole, as well as at the WW and $t\bar{t}$ thresholds, have the potential to reduce precision electroweak measurements to the per mille level or beyond, reducing current uncertainties by an order of magnitude. Future high-energy lepton colliders can also greatly constrain the effects of new physics as summarized through the Standard Model Effective Field Theory (SMEFT), reaching energy scales in four-fermion interactions of $50-100$ TeV or higher depending on the particular process and assumed center-of-mass energy.

QCD and Strong Interactions

- **Precision QCD:** Tremendous progress has been made since the last Snowmass exercise on precision calculations in QCD, determinations of the strong coupling constant, and use of jet substructure techniques to understand and predict experimental results − with implications for the HL-LHC and beyond. The non-perturbative input needed for track-based jet observables can now be computed at high precision. Energy correlation functions have emerged as a powerful tool to explore the scaling behavior of weakly coupled quarks and gluons, and the transition to the regime of free hadrons. The strong coupling constant at the Z-boson mass can be measured in the next decade with 0.4% precision, currently 0.8%, and with dedicated measurements at the Z-pole at future e^+e^- colliders, the precision can be reduced to 0.1%, enabling searches for small deviations from SM predictions that could signal the presence of new physics.
- **Hadronic Structure and Forward QCD:** Parton distribution functions (PDFs) are crucial for the interpretation of all hadron-collider experiments and often are the dominant source of uncertainty. New developments in lattice QCD hold the promise of first-principles computation of PDFs, and also related distributions, that can augment and enhance current phenomenological extractions of PDFs and provide input to new experiments. LHC experiments have opened access to a wide range of forward and diffractive processes, driving advances in relevant QCD theory, such as charting the gluon at very low x, revealing dynamics at high partonic densities, and testing Monte Carlo models for forward hadron production. The proposed Forward Physics Facility would extend the coverage at small x by almost two orders of magnitude at low Q, reaching down to $x \simeq 10^{-7}$.
- **Heavy Ions:** The relativistic heavy-ion program prioritizes the studies of the quark-gluon plasma (QGP), the partonic structure of nuclei, collectivity in small collision systems, and nuclear electromagnetic interactions. These measurements will greatly benefit from planned detector upgrades for ALICE, ATLAS, and CMS increasing, for example, capabilities for the detection of heavy-flavor mesons and quarkonia. Observations of heavy-flavor mesons elucidate mechanisms for their thermalization, Debye color screening, and recombination inside the quark-gluon plasma.

Physics Beyond the Standard Model

- **Model Specific Explorations:** Motivated by the question of the origin of the electroweak scale, composite Higgs and SUSY models remain very compelling and viable (though increasingly constrained) possibilities for physics beyond the SM. New high-energy colliders provide access to the new states predicted in these models. The highest mass reach is given by the FCC-hh or a 10 TeV scale muon collider, which provides opportunities to produce new physics particles with masses of order 10 TeV. These results complement and extend the precision measurements at lower energies which can be made at e^+e^- Higgs factories.
- **More General Explorations:** New states beyond the SM, including new gauge bosons, new fermions, or other resonances, are a feature of many extensions of the SM. High-energy colliders with a 10 TeV

partonic center-of-mass energy scale allow for the extension of expected HL-LHC bounds by an order of magnitude. For example, a 10 TeV muon collider will have the highest mass reach for a universal Z' with large couplings, uniquely probing masses $M_{Z'} > 100$ TeV. Simultaneously, high-luminosity Higgs factories and high-energy colliders can also probe light, exotic, and long-lived particle states with small coupling to SM particles. The direct new physics searches, together with the Higgs and electroweak physics will deepen our understanding of Nature to the next level.

- **Dark Matter at Colliders:** Collider searches for dark matter are complementary to astrophysical observations and direct-detection experiments, and potentially allow for a more precise determination of dark matter properties than available through those detection modes. Consistent with the results discussed above, the high luminosities and high energies of proposed new colliders provide a significant extension of results possible at the LHC to higher masses and/or lower couplings. For example, depending on the search strategies employed, WIMPs can be probed at high-energy lepton colliders up to close the kinematic limit for production, and at a 100 TeV hadron collider into the multi-TeV range, which can cover some of the most compelling benchmarks.

In summary, to pursue its scientific goals, the EF community proposes a combined strategy of precision measurements and high-energy exploration. Future lepton colliders starting at energies as low as the Z-pole up to a few TeV can shed substantial light on some of the key questions discussed in the ten topical group discussions. Ultimately, it will be crucial to find a way to carry out experiments at higher energies, directly probing and discovering new physics at the 10 TeV energy scale and beyond.

1.4.6 Instrumentation Frontier [9]

HEP experiments are always trying to collect larger data samples to improve the precision of measurements and the sensitivity of searches for previously unobserved phenomena. For colliding beam experiments, this is enabled by the ability to produce more intense beams and a consequently larger number of collisions per unit of time, which must be matched by improved and new instrumentation to deal with the larger, more complex data samples and the challenges of operating in harsh environments. In astrophysics, the development of enhanced instrumentation with new or improved capabilities is often the key to uncovering new regions of phase space.

Many solutions developed for experiments in this decade will not scale to meet the requirements of future experiments. Improved instrumentation is the key to progress in neutrino physics, collider physics, and the physics of the Cosmic and Rare Processes and Precision Measurement Frontiers. Many aspects now at the cutting edge of detector development were hardly present 10 years ago, including quantum sensors, machine learning, and picosecond-level timing. In many areas of HEP experiments, we are now at a point where completely new concepts are needed in order to enable scientific advancements. Evolutionary developments are no longer sufficient. This leads to a paradigm shift in which much more blue-sky R&D is needed. This is R&D with a high risk of failure, but also the potential to open completely new realms of sensitivity. Blue-sky R&D has been neglected over the last decade and funding and recognition for it, as well as the entire U.S. detector program, needs to increase in order to enable the science of the future. Funding for HEP instrumentation in the U.S., however, is actually declining.

In order to rejuvenate the instrumentation effort and to meet the challenging requirements for future scientific discoveries, the following actions are proposed:

- Advance performance limits of existing technologies and push new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

- Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers, and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

- Double the U.S. Detector R&D budget over the next five years and modify existing funding models to enable R&D Consortia along critical key technologies for the planned long-term science projects, sustaining the support for such collaborations for the needed duration and scale.

- Expand and sustain support for blue-sky, table-top R&D, and seed funding. Establish a separate review process for such pathfinder R&D.

- Develop and maintain critical facilities, centers, and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology road maps, other disciplines, and industry.

The work in the Topical Groups has culminated in the identification of a variety of specific R&D challenges and technologies that need to be pushed in order to reach the performance parameters required by the envisioned future physics program. They are summarized in the following:

Quantum Sensors Interest in quantum sensors has undergone explosive growth since Snowmass 2013 and they have been used in dark matter searches, searches for new forces (fifth force), electric dipole moments, variations in fundamental constants, and gravitational waves. The technologies include atom interferometers and atomic clocks, magnetometers, quantum calorimeters, and superconducting sensors. Thanks to the National Quantum Initiative, there is significant support for the development of such devices, but mostly outside of HEP. It is highly desirable to develop mechanisms to support interactions with other disciplines to enable collaborations with fields with expertise in quantum sensors and to facilitate interactions to support theoretical work to address issues of materials and measurement methods.

Photon Detectors In the last decade, major developments have occurred in the detection of photons, in particular the counting of single photons over a wide frequency range from the infrared to the ultraviolet. Many of the technologies being developed need additional work, which will be the focus of R&D for the next decade, to enable large area arrays and to improve the energy resolution, timing, noise (dark counts), and wavelength coverage. A significant achievement has been the solution for the detection of photons in liquid argon by use of Arapuca light traps followed by readout using SiPMs. Additional new ideas are being developed based on novel light collectors called dichroicons, based on Winston cones using dichroic mirrors, allowing Cherenkov and scintillation light to be separated and focused on separate photomultiplier tubes, individually optimized for their respective wavelengths. Another significant achievement of the last decade is the development and commercialization of Large Area Picosecond Photodetectors, LAPPDs. Sensors being developed include:

- Superconducting sensors: Microwave Kinetic Inductance Detectors (MKIDs); Transition-Edge Sensors (TESs); and Superconducting Nanowire Single Photon Detectors (SNSPDs);

- Semiconducting sensors: Skipper-CCDs (including in CMOS); Photon-to-Digital Converters (PDCs); and extended wavelength coverage Germanium semiconductors with enhanced UV sensitivity.

Solid State Detectors and Tracking As collision rates increase and the number of interactions per crossing grows, tracking based on solid-state detectors, mainly silicon, provides the segmentation and radiation resistance necessary to meet the needs of the next generation of experiments. The focus is now on developing 4-dimensional trackers with timing resolutions of 10-30 ps and spatial resolution of a few μm. Improvements in the readout electronics, including radiation hardness and management of the material and power budget, are important areas where R&D is necessary.

Candidates for novel sensors are silicon or diamond detectors with "3D technology"; sensors with Four-Dimensional Tracking – tracking detectors with 10-30 ps timing resolution, in addition to excellent position resolution. The overall detector system should contain a sensor with short drift time, high signal-to-noise, limited thickness in the path of a MIP to reduce the Landau fluctuations, and small TDC bin size; monolithic Active Pixel Sensors (MAPS), in which charge collection and readout circuitry are combined in the same pixel, which has been shown to be a promising technology for high-granularity, low material budget, and low-noise detector systems. Concerning integration, conventional bump bonding has been used for many years to connect high-density pixel sensors to readout ASICs. Much smaller pixel pitches and consequently finer connections are needed for future experiments. Advanced packaging techniques will be required. 3D integration can solve many of these problems and is being developed in industry. Detector mechanics will play a significant role in the performance of future detectors. Material savings using novel approaches have the potential of reduction on the order of 30-50%.

Trigger and DAQ The challenge for future data-intensive physics facilities lies in the reduction of the flow of data through a combination of sophisticated event selections in the form of high-performance triggers and improved data representation through compression and calculation of high-level quantities. These tasks must be performed with low latency (i.e. in real-time) and often in extreme environments including high radiation, high magnetic fields, and cryogenic temperatures. Developing the trigger and data acquisition (TDAQ) systems needed by future experiments will rely on innovations in key areas, including the application of Machine Learning (ML) to TDAQ systems, particularly in the co-design of hardware and software to apply ML algorithms to real-time hardware and for other novel uses to improve the operational efficiency and sensitivity to new physics of future experiments. One key recommendation is to create a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offer opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and the development and maintenance of an accessible knowledge base that crosses experiment-project boundaries.

Micropattern Gaseous Detectors (MPGDs) Gaseous Detectors are the primary choice for cost-effective instrumentation of large areas and for continuous tracking of charged particles with minimal detector material. MPGDs are gas avalanche devices with order O(100 μm) feature size, enabled by the advent of modern photolithographic techniques. Current MPGD technologies include the Gas Electron Multiplier, the Micro-Mesh Gaseous Structure, Thick GEMs, also referred to as Large Electron Multipliers, the Resistive Plate WELL, the GEM-derived architecture, the Micro-Pixel Gas Chamber, and the integrated pixel readout. MPGDs are used in many currently operating experiments and are planned for future experiments in particle physics and nuclear physics. The global HEP community would benefit from coordination of U.S. strategy with the ECFA Detector R&D implementation process in Europe; and in order to maintain and expand U.S. expertise on MPGDs, the NP and HEP communities would benefit strongly from a joint MPGD development and prototyping facility in the U.S..

Calorimetry The precision energy measurement requirements of future physics programs are stimulating innovation in particle flow and dual readout systems. The increasing availability of precise timing is adding an important new dimension to system implementation, while the development of a range of fast, radiation-hard active materials is leading to increased flexibility and exciting possibilities for calorimeter system designs.

Future calorimetry at fixed target and colliding beam experiments should be fundamentally multidimensional, providing shower position, time, energy, and a detailed look at shower constituents through the exploitation of an application-specific combination of particle flow techniques, materials with intrinsically good time or energy resolution, and/or dual readout techniques. Sustained R&D is needed to move multidimensional calorimeters from the prototype stage to realistic detectors. Scaling to hundreds of thousands or tens of millions of channels while maintaining the required quality is a huge challenge. Effective partnerships with chemists, materials scientists, industries large and small, and radiation facilities must be continued and strengthened to explore the landscape of materials that enable precision calorimetry and to lower the cost for future applications. **Readout Electronics and ASICs** Increased channel count and granularity, driven by the requirements of particle flow calorimetry as much as by tracking, and the need to operate in very harsh environments, for example in high radiation or at cryogenic temperatures, has increased to need for custom readout electronics and ASICs. The development of ASICs requires access to very highly specialized electronics engineers and technicians and physicists with some training in this area. There are some overarching goals for advancing the field of readout and ASICs. Among those are to improve mechanisms for shared access to advanced technology providing broader access by the community to foster real exchange of information and accelerate development; create frameworks and platforms for easy access to design tools; develop specialized online resources for the HEP community (e.g. system simulations and design repositories);and and provide the basis for true co-design R&D efforts from simulation to verification and implementation.

Noble element Detectors Many neutrino and dark matter experiments employ noble elements in liquid, gaseous, or solid phases because they can provide large target volumes, with low backgrounds, and provide multiple signal paths for event detection and classification, including ionization as well as scintillation and Cerenkov light (photons). Key needs are to enhance and combine existing modalities (light and charge) to increase signal-to-noise and reconstruction fidelity; develop new modalities for signal detection in noble elements, including methods based on ion drift, metastable fluids, solid-phase detectors, and dissolved targets; and address challenges in scaling technologies including material purification, background mitigation, large-area readout, and magnetization.

Cross-cutting and Systems Integration Presently U.S. funding for Advanced Detector R&D is institute-based rather than collaboration-based. Yet collaborations are more essential than ever to leadership in Detector R&D technology and funding constraints have limited the opportunity to establish significant collaboration. Funding for the DOE's KA25 Detector R&D program should be increased significantly (2-5X) to enable the establishment of collaborative R&D programs that can address Grand Challenges and pursue blue-sky concepts. We recommend that funding for key technical personnel essential to these capabilities be considered on equal footing with the physicists. It is essential that adequate resources be provided to support more speculative blue-sky R&D. The U.S. HEP community should establish a robust collaborative research program that includes both participation in international RD collaborations and the establishment of domestic Detector R&D consortia. Facilities are required to advance all detector technologies. Test beams and irradiation facilities allow users to test the performance and lifetime of their detectors under realistic conditions. It is important that the energy, intensity, particle composition, and time structure of the beams are adequate for the detector needs of the next generation. Cryogenic Test Facilities are also required. The operation of sensors and systems at ultra-low temperatures is a major growth field, but one which necessarily has a high barrier for entry due to the relatively high cost of equipment, not just for the cooling platform itself but also for associated measurement equipment and electronics, and a knowledge gap in the operation and engineering of devices and systems at cryogenic temperatures. Facilities (mainly at U.S. National Labs) are a vital element of detector technology development and should be supported. Present gaps should be eliminated. Finally, multidisciplinary problems are prevalent in many areas of instrumentation development. Multidisciplinary work has funding, recruiting, and career development challenges that new R&D frameworks could alleviate.

Radiodetection Cosmic rays, neutrinos, and gamma rays are all important probes of astroparticle physics and high energy physics. They require large volumes of natural material that can be monitored to study these very rare events. Standard targets are mountains, the Earth's crust, large volumes of ice, or the atmosphere, the latter two of which are being actively pursued. Ice is transparent to radio-frequency signals over distances of order 1km. Approaches under study for radio detection of cosmic particles include Askaryan emission, geomagnetic detection, and radar. R&D is required to optimize designs and reduce cost, optimize power consumption and simplify electronics design, especially for large extended arrays, and prepare the way for future large experiments by undertaking pathfinder experiments for new mm-wave detectors with high channel density.

Detector instrumentation is at the heart of scientific discoveries. Cutting-edge technologies enable U.S. particle physics to play a leading role worldwide. The Instrumentation Frontier report summarizes the current status of instrumentation for High Energy Physics, the challenges and needs of future experiments, and indicates the high-priority research areas.

1.4.7 Neutrino Frontier [10]

Neutrinos, the neutral electroweak partners of the charged leptons, are predicted to be massless in the SM. The discovery that neutrinos of one flavor oscillate into another flavor as they propagate is a clear indication that there is physics beyond the SM. The study of neutrinos and their properties is therefore an essential component of the U.S. HEP program in the coming decades. The physics questions which drive these investigations include:

- **How are the neutrino masses ordered?** In particular, is the electron neutrino mostly made up of the heaviest mass eigenstate or not?
- **What are the values of the neutrino masses?** While oscillation measurements only constrain neutrino mass-squared differences, how well can laboratory-based or cosmological observations constrain the overall mass scale?
- **What is the origin of the neutrino masses?** Do neutrinos get mass via the same mechanism as the other quarks and leptons or does their mass-generation mechanism involve new physics?
- **Are neutrinos their own anti-particles?** Are neutrinos Dirac or Majorana particles?
- **Do neutrinos and antineutrinos oscillate differently?** Is there CP violation in the neutrino sector and, if there is, could it play a role in the generation of the matter-antimatter asymmetry in the early universe?
- **Is the three-flavor picture of neutrino oscillation complete?** Are there more neutrinos, potentially with different electroweak properties?
- **Do neutrinos interact in novel ways, or with new and so-far undiscovered particles?** Are there additional neutrino properties related to dark matter or new physics at low energy scales?
- **Using neutrinos as a window on the universe, what will we see?** How can we use neutrinos as probes into some of the most energetic and still-mysterious processes in the universe?

Since neutrinos interact so weakly, their properties can only be studied in sensitive experiments with a large target mass where the few neutrino interactions can be confidently measured and precisely characterized in the presence of backgrounds. Neutrino oscillation measurements in particular can be effectively carried out using GeV-scale neutrino beams generated using high-intensity protons. Neutrino fluxes are measured at near detectors before propagating over long baselines to large underground detectors.

The DUNE collaboration was formed to realize the 2014 P5 vision of a best-in-class long-baseline experiment based at Fermilab. The DUNE R&D program, propelled by the development of large-scale liquid-argon detectors in the U.S. and Europe, in particular through the CERN Neutrino Platform, has demonstrated the power and feasibility of this technique.

The DUNE program will unfold in parallel with the Hyper-Kamiokande (HK) long-baseline experiment in Japan. The HK experiment plans to utilize the upgraded J-PARC 1.3 MW proton beam, an upgraded near detector, a proposed new intermediate detector to be installed ~ 1 km away from the neutrino production target, and a new 260 kt water-Cherenkov far detector located 295 km away from the neutrino source. HK will have a strong sensitivity to CP violation for much of the parameter space, assuming the neutrino mass ordering is known. While HK's design parameters will make mass-ordering determination difficult using its accelerator neutrino data sample alone, a simultaneous fit to the accelerator and atmospheric neutrino data is expected to significantly enhance sensitivity to oscillation parameters. Civil construction for the HK tank is underway, with data-taking scheduled to start in 2027.

DUNE will be built in two phases. Phase I includes completion of the Long-Baseline Neutrino (LBNF) and the Sanford Underground Research Facility (SURF) in South Dakota, 1300 km from the neutrino source at Fermilab and about 1475 m underground, including far site facilities to accommodate four far detector modules (FDs), each with a mass of at least 10-kt (fiducial), and installation of the first two FD modules, as well as near-site facilities to support the full (Phase II) near detector (ND), installation of a minimal suite of near detectors, and a 1.2 MW source proton beam at FNAL that can be upgraded to 2.4 MW. LBNF will be completed before the beginning of DUNE Phase I data-taking in the late 2020s. The Phase I configuration is sufficient for early physics goals, including the determination of the neutrino mass ordering.

DUNE Phase II is required to achieve the precision neutrino oscillation physics goals laid out by the last P5 and is the U.S. HEP neutrino community's highest priority project for 2030–2040. The Phase II project has three components: an upgrade or replacement of the Fermilab 8 GeV Booster to deliver 2.4 MW to the DUNE target and possibly to provide beams for other experiments; the construction of an additional 20 kt (fiducial) of far-detectors at SURF; and the full, highly capable, near-detector complex at FNAL to control the systematic uncertainties for the far detector measurements. The full DUNE program will perform definitive studies of neutrino oscillations, test the three-flavor paradigm, search for new neutrino interactions, resolve the mass ordering question, and have the ability to observe CP violation if it is present in neutrino oscillation.

The Neutrino Frontier program includes a broad scope of activities spanning the full range of scales, including DUNE as a major international program with more than a thousand collaborators; medium-scale experiments such as those making up the short-baseline neutrino program; contributions to international experiments; smaller-scale experiments at accelerators, reactors, and spallation neutron sources; down to tabletop experiments and blue-sky R&D activities. Many examples are described in the Topical Group reports and a comprehensive list of Neutrino Frontier experiments is provided in the Frontier Report from information provided by the community members. All of these efforts have the potential to make paradigm-changing discoveries or innovations or provide necessary inputs to experiments that will make these discoveries, and they will work in synergy to address the science Drivers described above.

A neutrino program incorporating the breadth and diversity of efforts at different scales does more than just increase the chances for major discoveries. Such a program is healthy for future scientific progress by making space for creative thinking, and also provides training opportunities to ensure a capable workforce in the long term. The last P5 report recommended: "Maintain a program of projects of all scales, from the largest international projects to mid and small-scale projects". The Neutrino Frontier endorses continued and enhanced support of this recommendation.

Cross-pollination between Frontiers and other fields of science offers further opportunities. Physics topics within the Neutrino Frontier overlap strongly with each other, and also with other Frontiers. Examples include instrumentation for dark matter and neutrinoless double beta decay searches; the study of neutrino-nucleus interactions; the detection of high-energy neutrinos with far forward experiments at the LHC; and the Cosmic Frontier programs that provide insight into neutrino properties from cosmological observables.

The Neutrino Frontier includes the following Topical Groups: NF01, Neutrino Oscillations; NF02, Understanding Experimental Neutrino Anomalies; NF03, Beyond the Standard Model (BSM); NF04, Neutrinos from natural sources; NF05, Neutrino properties; NF06, Neutrino Interaction Cross Sections; NF07, Applications; NF08 $\rightarrow$ TF11, Theory of Neutrino Physics (a topical group shared with the Theory Frontier); NF09, Artificial Neutrino Sources; and NF10, Neutrino Detectors.

To summarize, the Neutrino Frontier recommends:

- A future neutrino program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.
- Completion of existing experiments and execution of DUNE in its full scope is critical for addressing the NF science Drivers.
- Directed R&D needs to be supported to exploit the new and broader opportunities presented by DUNE Phase II.
- In order to reap the full scientific benefits from future neutrino experiments, strong and continued support for neutrino theory is needed.
- The Neutrino Frontier, with its strong connections across HEP and beyond, has a special responsibility to contribute to leadership for a cohesive, HEP-wide strategic plan for DEI and community engagement.

A description of the work of the Topical Groups that contributed to the final Neutrino Frontier vision is given below:

Theory and Motivation A robust neutrino theory and phenomenology effort is required in order to exploit the unique probes of fundamental physics provided by neutrino experiments to interpret the data, build models to accommodate new phenomena, provide guidance for future experiments, and connect the new discoveries in neutrino physics to other areas of particle and nuclear physics, astrophysics, and cosmology. For precision measurements of the three-flavor picture, for example, theory provides the necessary work to produce a precise description of relatively low-energy neutrino-nucleon and neutrino-nucleus scattering. Theory is also making links between neutrino properties, established or conjectured, and cosmology. An increase in support for the neutrino theory effort is well justified.

Three-Flavor Neutrino Oscillation The three primary goals of the coming years of neutrino oscillation measurements are: to determine the "neutrino mass ordering," which is defined by the sign of Δm^2_{31}; to determine whether θ_{23} is more than or less than 45° and how close to maximal it is, known as the

"octant" question; and to measure δ_{CP} and determine whether $\sin\delta_{CP} = 0$ can be excluded or not. The next-generation experiments, DUNE/LBNF at Fermilab/SURF and the Hyper-Kamiokande experiment in Japan are designed to achieve the necessary statistical precision to answer the above questions over the full parameter space. JUNO, a large liquid scintillator experiment in China, and IceCube-Gen2 will also contribute to the knowledge of oscillation parameters.

Physics Beyond the Standard Model and Understanding Experimental Neutrino Anomalies The rapidly expanding field of searching for BSM neutrino physics now includes: Heavy Neutral Lepton (HNLs) searches, expanding the continuing effort to understand the neutrino "anomalies"; neutrino flavor and neutrino scattering; and dark matter and baryon number violation searches (BSM physics searches that can be accomplished using neutrino detectors). The last P5 supported experiments aimed at understanding the LSND, MiniBooNE, and reactor anomalies. Should the interpretations converge, the short-baseline experimental and theoretical landscape will shift, with subsequent priorities depending heavily on what is learned about the various hypothesized anomaly origins. It is therefore essential that resources are available to enable adaptation to developments during the next P5 period.

Neutrinos as Terrestrial and Astrophysical Messengers Neutrinos, by virtue of their weak interactions, probe otherwise inaccessible sources. They serve as terrestrial and astrophysical messengers, providing unique information about the nature of the sources themselves. In conjunction with other types of emissions (photons, gravitational waves, charged particles) astrophysical neutrinos provide a deeper and richer scientific story. Cosmological studies also provide important contributions to our understanding of neutrino properties, with sensitivity to the number of neutrinos, the sum of their masses, and potential new neutrino interactions. Current-generation detectors have measured neutrinos from a few hundred keV up to the PeV regime. Expanding outside of this energy interval is unexplored territory, requiring novel technology.

Neutrino Properties KATRIN and cosmological surveys will eventually be sensitive to the absolute mass scale of neutrinos down to $\sim$0.01 eV. The coming ton-scale generation of neutrinoless double beta-decay experiments will probe effective Majorana neutrino masses as small as 10 meV. The neutrino community is pursuing a thriving R&D program for beyond ton-scale searches; there is a strong consensus for building a ton-scale double beta-decay experiment with U.S. leadership, multi-agency, and international support, as well as interest in continuing participation in other programs worldwide. Neutrinos should have small electromagnetic interactions induced by radiative corrections that can be probed in the next generation of elastic neutrino-electron scattering and CEνNS experiments at accelerators and reactors. Other exotic neutrino properties, including those that violate fundamental SM symmetries or have gravitational interactions that violate the equivalence principle, are all potentially observable.

Neutrino Interactions A thorough theoretical and phenomenological understanding of neutrino cross sections over a wide range of energies and targets is crucial for the successful execution of the entire neutrino physics program. This understanding must be captured in event generators; these event generators must be maintained and updated whenever new measurements or theories become available, but this work is often undervalued relative to other activities. Low-energy (< 0.1 GeV) neutrino cross sections are relevant for studying solar, reactor, and supernova neutrinos. Stopped-pion neutrinos can be used to study, through processes like CEνNS, fundamental properties of neutrino weak interactions. Long-baseline experiments make use of neutrinos in the few-GeV range and the need for understanding the cross sections in this regime is critical for the interpretation of oscillation experiments. New information will come from experiments using electrons as well as direct neutrino cross-section measurements by short-baseline experiments, near detectors in long-baseline experiments, and dedicated neutrino scattering experiments. High-energy cross sections (from a few hundred GeV to greater than the TeV scale) are relevant for high-energy astrophysical neutrinos. No laboratory neutrino cross-section data are yet available for energies above about 350 GeV (although some

measurements with astrophysical neutrinos have been done). Detection of neutrino interactions in the far forward region at the LHC will extend the laboratory reach into the TeV scale.

Computing Many of the neutrino community's computing issues are shared by experiments on the other Frontiers, such as the change to heterogeneous computing hardware and the dependence on HPCs. The need for data preservation is also crucial since cross-section measurements will be taken over time but the most detailed use of them will be after DUNE has acquired enough data to reach the 1% systematic uncertainty level. Special considerations include the need for strong and responsive support for GEANT4 (or successors), the integration of new experimental results and theory into event generators, and in general the maintenance of software over the long duration of the experiment and beyond. Machine learning has been embedded in the neutrino community for a long time but a new element is a reliance on externally developed frameworks, which provides many advantages but requires work to develop and maintain interfaces. DUNE also has a different data profile than many other HEP experiments so its storage requirements and access patterns may present special challenges.

Artificial Neutrino Sources The primary artificial neutrino sources of wide use in the Neutrino Frontier are accelerator-produced beams. Beam powers of hundreds of kW have been achieved at FNAL and J-PARC and upgrades to MW beams are planned for DUNE and HK. Nuclear reactors have also had a central role in experimental neutrino physics ever since the discovery of these elusive particles in 1956; they are the most intense source of MeV-scale electron antineutrinos. Spallation neutron sources such as the Spallation Neutron Source at Oak Ridge National Laboratory provide, as a by-product, the most intense accelerator-based sources of neutrinos in the world, and are particularly important for a wide variety of neutrino physics measurements. The LHC produces neutrinos and, with instrumentation downstream of the collision region at Point 1, the FASERν collaboration recently reported the first observations of neutrinos from a collider. There are many other novel neutrino sources under consideration, including neutrinos produced from muon beams and neutrinos produced by proton cyclotrons.

Detectors Neutrino physics spans an enormous range of energies and scales from keV to TeV. This means that a broad spectrum of detection technologies is required. Several areas have attracted large community interest, including expanding programs aimed at improving liquid and gaseous noble element TPCs; pursuing hybrid Cherenkov/scintillation detectors; optimizing low-threshold neutrino detectors to achieve even lower energy thresholds and better background rejection techniques as well as moving toward larger detector masses; developing technologies for neutrino detection at the PeV scale and beyond; and developing in collaboration with the Cosmic Frontier new dark-matter detectors. Both the development of new noble liquid and gas detectors and low-threshold detectors of various types can produce devices that are useful for both the Neutrino Frontier and the Cosmic Frontier.

Applications Somewhat surprisingly, given the inherent difficulty of neutrino detection, the direct application of neutrinos to advance other fields of research or solve societal problems is also feasible. Better knowledge of reactor neutrino emission will improve our understanding of the physics of reactors and enables applications to nuclear non-proliferation safeguards, nuclear security, and arms control. Neutrino emission can also be used to probe the Earth's interior. Given that neutrino physics represents a major component of the U.S. program, there are opportunities for leadership in addressing societal issues. These topics are discussed in detail in the Community Engagement Frontier report.

To summarize, if the three-flavor paradigm is sufficient to fully describe the neutrino sector, it will take approximately the next two decades to fill in the main features of the picture. In parallel, studies of the anomalies and the search for BSM physics will continue. Astrophysical neutrinos will continue to bring new information. Neutrino physicists will continue to develop new instrumentation, new sources, new analysis methods and tools, and new concepts to position themselves for physics well beyond DUNE.

The physics of neutrinos and the physics that can be done with neutrinos extends from sub-eV to EeV – across eighteen orders of magnitude – and touches nearly every other area of particle physics. The U.S. neutrino program is poised for an exciting future. The path is clear for the next P5 period and the decade beyond it.

1.4.8 Rare Processes and Precision Measurements Frontier [11]

The Rare Processes and Precision Measurements Frontier (RPF) encompasses searches for extremely rare processes or tiny deviations from the SM that can be studied with intense sources and high-precision detectors. In Snowmass 2013, these topics were combined with neutrino physics to form the "Intensity Frontier". For Snowmass 2021, neutrino physics was designated as a frontier in its own right, with the remaining very broad and diverse collection of topics constituting RPF. Searches for rare flavor transition processes and precision measurements are indispensable probes of flavor and fundamental symmetries and provide insights into physics that manifests itself at higher energy or through weaker interactions than those directly accessible at high-energy colliders. This program includes very small-scale experiments, as well as medium- and large-scale experiments.

The Rare Processes and Precision Measurements Frontier is currently working on two mid-sized U.S. projects at Fermilab endorsed by P5 in 2014, namely the Muon $g-2$ experiment, which is nearing completion, and the Mu2e experiment, which is under construction. The program also has important investments in flavor physics through the support of the Belle II experiment in Japan and LHCb at CERN. Priorities for the next few years are to complete the analysis of the Muon $g-2$ experiment, begin taking data with Mu2e, and continue taking and analyzing data at Belle II and LHCb.

Since Snowmass 2013, several important results have emerged from RPF experiments. The initial results from the Muon $g-2$ experiment are consistent with the result obtained at BNL in 1997, now with increased precision, and much more data has since been taken and will soon be analyzed. Taken at face value, the gap between experiment and (current) theory is now greater than 4σ, a tantalizing hint for physics beyond the Standard Model. However, lattice QCD calculations of the hadronic corrections to muon $g-2$ are rapidly improving in precision. In light of the first results indicating puzzling tensions with the current SM prediction, it will be important to see if lattice QCD results, once they have been cross-checked against each other, agree with the data-driven evaluation on which the current SM prediction is based. Since 2013, several measurements from LHCb and Belle II in B-meson decays that involve leptons in the final state have also shown tensions with predictions of the SM. These include $b \to s l^+ l^-$ and $b \to c\tau\overline{\nu}$ transitions at BABAR, Belle, and LHCb, and in rare and forbidden decays such as $b \to s\nu\overline{\nu}$ or $B_s \to l^+ l^-$ in LHCb. While no single measurement has reached 5σ, there seems to be an emerging pattern that could be explained by the existence of a new scalar particle or leptoquarks. This highlights the potential of RPF for the discovery of BSM physics.

Looking ahead to the next decade and beyond, the Frontier developed a broad community consensus consisting of six central points (unordered and intertwined)

- The threefold replication of the generations, combined with the unexplained pattern of masses of quarks and leptons, spanning several orders of magnitude, is a central mystery of particle physics. Flavor physics has two main goals. The first objective aims at uncovering the underlying reason for family replication and its different properties. The second encompasses the study of the rich of decays of different flavor species available for experimental observation and allows us to probe deviations from SM expectations with a multiplicity of approaches. The search to understand the physics of flavors and

generations is central to both physics programs articulated by the Neutrino and Rare Processes and Precision Measurements Frontiers, but this centrality is hidden in the structure of our current science Drivers. As a result of the breadth of flavor physics, its potential for discovering BSM physics, and the hints in the current data, the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a **new science Driver: flavor physics as a tool for discovery**.

- The U.S. should support the LHCb Phase-II upgrades and Belle II. These experiments are broad, powerful, and irreplaceable probes of flavor physics along with topics relevant to all the Frontiers. These experiments pursue complementary research programs that utilize different beams and detection techniques to explore a vast array of new physics in beauty, charm, and rare tau decays. In addition, they investigate the patterns of bound states as the manifestation of the richness of QCD in its non-perturbative regime and contribute significantly to the exploration of the dark sector.

- We should select a portfolio of accelerator-based dark sector experiments that are well-motivated, unique, and affordable. Many possibilities have been identified and studied during the Snowmass process. P5 needs to support this physics, with a consequent process through which the community, DOE, and NSF select an efficient and effective subset of the opportunities using the Dark Matter New Initiatives (DMNI) studies as input.

- Experiments investigating charged lepton flavor violation and lepton number violation in the muon sector can probe mass scales far beyond the direct reach of colliders, as well as explore the nature of the flavor physics issues central to HEP. The PIP-II 800-MeV SRF proton linac under construction at FNAL, if upgraded to CW beam capability with a total average beam power of up to O(1 MW), would enable a new muon program at an unprecedented intensity that could increase the discovery potential of such experiments by at least an order of magnitude. The U.S. should support vigorous R&D in order to realize this program.

- The theory efforts that guide and enable these investigations, while not "projects" in themselves, should be vigorously supported by P5. RPF relies on the techniques of and guidance from Effective Field Theories (EFTs), as well as calculations of quantities that provide precise and unbiased results that can be systematically improved as needed, such as Lattice QCD. Precision measurements of deviations from the SM, instead of the direct observation of new particles, require these methods. In addition, theory-experiment collaboration in developing new experimental approaches has been at the foundation of much of the progress in dark sector searches and is vital to this growing field.

- A portfolio of experiments of different cost and time scales is an integral part of the RPF physics program. Promising experiments include:

  - experiments measuring electric dipole moments, in particular, the proton EDM measurement in a storage ring, along with experiments exploiting synergies with AMO techniques to examine fundamental symmetries;
  - experiments probing rare light meson decays, such as REDTOP;
  - involvement of the U.S. experimental community in the vibrant international program at both CERN and J-PARC studying rare K decays;
  - the PIONEER experiment at PSI which will study lepton universality in the muon and electron generations.

- We also stress that small and medium-sized multipurpose experiments can provide training for early career researchers over many stages of an experiment, from proposal-writing to design and construction to publication, exemplified by the Fermilab g−2 or the quark flavor experiments, that allow junior scientists to combine instrument or computationally intensive tasks with physics analysis contributions

in their portfolio. In addition, the relatively small sizes of these experiments allow for less hierarchical organization, with a broad array of leadership opportunities. A commitment to mentor early career scientists in a supportive and inclusive environment should help to guide our programmatic choices.

This Frontier connects to several other Frontiers. It connects to Nuclear Physics and AMO, especially in regard to EDM searches, which can be done with nucleons, atoms, or molecules and are really low-energy experiments. Since some of the experiments use storage rings or special accelerator facilities, there is a strong link to the Accelerator Frontier. The diversity of the experiments leads also to the need for specialized instrumentation, providing a strong connection to the Instrumentation Frontier.

The material developed in the Topical Groups that is used as input to this consensus is very briefly summarized in the paragraphs below. Many more details are given in the RPF summary report and the individual Topical Subgroup reports and white papers.

Weak decays of b and c quarks Studies of heavy-flavored hadrons provide rich, diverse, and model-independent probes for new physics at energy scales far beyond what is directly accessible. Heavy-flavor physics is crucial to our search for new physics in the upcoming 10–20 years, important advances are expected through a highly synergistic program of experiments: LHCb and its planned upgrades at the LHC, Belle II at the SuperKEKB asymmetric e^+e^- collider, and the e^+e^- charm factories BESIII and STCF. In particular, Belle II and LHCb have the unique potential to unveil new physics by confirming intriguing hints of deviations from the SM that have been recently observed in $b \to s\ell^+\ell^-$ and $b \to c\tau\overline{\nu}$ transitions at BABAR, Belle, and LHCb, or finding new unexpected outcomes in the study of rare and forbidden decays such as $b \to s\nu\overline{\nu}$ or $B_{(s)} \to \ell^+\ell^-$. In addition, the continuing refinement of the studies of quark mixing, flavor oscillations, and CP violation may unveil subtle deviations from SM expectations. Farther into the future, the experimental program can be extended at the e^+e^- circular colliders proposed for precision studies of the Higgs boson. The U.S. flavor community is well-positioned to lead key aspects of the physics, computing, and detector construction in all of these experimental programs. Theoretical efforts that inspire and elucidate the fundamental impact of experimental findings are crucial to success and should be supported. The lepton universality and other stringent tests foreseen in these experiments and their upgrades are discussed in the b and c topical group reports.

Weak decays of strange and light quarks Studies of the light quarks include precision measurements of both flavor-conserving and flavor-violating decays of pions, kaons, hyperons, and η/η' mesons. Tests of new physics through checks of the first column unitarity of the CKM matrix, along with lepton flavor/number and lepton universality tests, have revealed experimental anomalies. These anomalies require additional experimental and theoretical studies of the light quark systems to conclusively assess their impact.

Fundamental Physics in Small Experiments The study of static properties of elementary particles (electric and magnetic moments) and the fundamental symmetries (C, P, T, and their combinations, along with basic probes of Lorentz symmetry), all probe energy scales approaching the Planck scale. The experiments addressing this physics are of small to intermediate size and sometimes involve methods not traditionally considered high-energy physics. Nonetheless, in subjects such as $n\overline{n}$ oscillations, EDMs, and neutrinoless double beta-decay, the Frontier worked to identify ways to develop a synergistic physics program that exploits the expertise of the high-energy physics community, the relevant AMO and nuclear physics communities, and the scientists performing such research. Storage ring EDM experiments are an exciting opportunity, and proton storage ring experiments might reach 10^{-29} e-cm. Low-energy antimatter gravity tests using muonium could be performed at the AMF facility described in the RPF Frontier report [11], and these developments are also synergistic with possible efforts for precision measurements of the muonium spectrum and searches for muonium-antimuonium oscillations. PIONEER can study lepton universality in charged

pion decay to 0.01% precision, probing heavy neutral leptons and dark sector particles up to PeV mass scales, and complement universality tests in b-decays.

Baryon and Lepton Number Violating Processes Experimental and theoretical research in baryon- or lepton-number violation (such as proton decay, $n-\overline{n}$ oscillations, and searches for $0\nu2\beta$ decays) is traditionally supported by nuclear physics (NP). These efforts share many of the same intellectual problems, methods, and people with HEP. Unfortunately, the NP/HEP separation produces barriers that make it difficult for researchers at the border. Studies of neutrons are another avenue of opportunity for profound discoveries. One particular opportunity of note is the study of $n\overline{n}$ oscillations. The proposed NNBar experiment at the ESS could reach a limit of $\tau_{n\overline{n}} \sim 10^{9-10}$s. "Mirror neutrons", $n \to n'$ oscillations, have been ruled out as an explanation of the discrepancy between neutron lifetimes measured with cold and ultracold neutrons, but improved sensitivity to this phenomenon is possible at the HIBEAM program at the ESS. It is worth noting that studies of baryon-number violating decays of heavy flavors are uniquely being carried out in dedicated flavor experiments, such as LHCb and Belle II.

Charged Lepton Flavor Violation (electrons, muons, and taus) In contrast to neutrinos and quarks, charged lepton flavor violating/violation (CLFV) interactions that do not conserve lepton family number, have never been observed. The archetypal CLFV decay is $\mu \to e\gamma$ (with no emitted neutrinos). Muons play a unique role in CLFV searches because we can make intense beams of muons and achieve the highest statistical sensitivity. In muon-to-electron conversion, $\mu^- N \to e^- N$,the Mu2e experiment at Fermilab will reach its goal of $R_{\mu e} < 8 \times 10^{-17}$ at 90% CL by the end of the decade. A factor of ten upgrade from Mu2e, Mu2e-II, needs R&D effort to both improve the limit and change the physics probed with a different target nucleus, most likely Ti. The proposed Advanced Muon Facility (AMF) exploits the PIP-II CW beam upgrade augmented by new rings. This facility would allow us to examine both $\mu^- N \to e^- N$ and $\mu \to 3e$, as well as $\mu^- N \to e^+ N'$ and muonium oscillation studies, at rates far beyond those achievable at any other planned facility; here Detector R&D is essential to use the rates available at PIP-II. AMF would also enable a dark matter experiment. AMF itself also requires significant R&D.

Dark Sector Studies at High Intensities Because dark sectors are generically weakly coupled to ordinary matter, and because they can naturally have (light) masses ranging from roughly the electron mass to the proton mass and respect the Standard Model's symmetries, they are only mildly constrained by high-energy collider data and precision atomic measurements. Intensity Frontier experiments provide opportunities to carry out experimental studies of the dark sector with possible access to specific dark matter candidates. Existing large multipurpose detectors, especially Belle II and LHCb, can be used to study dark-sector states as well as dedicated efforts at high-intensity accelerators. The DarkMatter New Initiative (DMNI) report has given initial support to two experiments, and a promising set of experiments has been identified since the last P5 report. A broader, coordinated program is emerging from this initial work. Dark-sector theory will also provide critical guidance. A key consensus of the RPF is that the U.S. should develop a portfolio of DM experiments using intense beams.

Hadron Spectroscopy Hadron spectroscopy examines the description of the spectrum of hadrons from non-perturbative QCD. With the availability of intense sources of hadrons, many new states composed of quarks and gluons have been discovered by LHCb, Belle/Belle II, BESIII, and other experiments. Several of these do not fit among conventional hadronic states composed of quark-anti-quark pairs (mesons) or three quarks (baryons). New exotic states, such as tetra- and pentaquarks, hybrids, etc., are added every year. The nature of these states is not clear. Configurations such as compact multiquark states, hadron molecules, or even linear combinations of such components, are possible and require careful experimental measurements to disentangle. Detailed studies require very large samples of these hadrons and need high luminosity colliders or intense beams.

RPF uses the techniques of many accelerators and experiments to search for new physics and do precision SM tests with diverse and complementary approaches. The major themes of this Frontier that emerged during the Snowmass process have been summarized here; the range and power of the RPF program are unique and several experiments that we examined encompass the flexibility that enables them to elucidate unexpected observations regardless of where they are found.

1.4.9 Theory Frontier [12]

Theoretical particle physics seeks to provide a predictive mathematical description of matter, energy, space, and time that synthesizes our knowledge of the universe, analyzes and interprets existing experimental results, and motivates future experimental investigation. Theory connects particle physics to other areas of physics and extends the boundaries of our understanding. Together, fundamental, phenomenological, and computational theory form a vibrant interconnected ecosystem whose health is essential to all aspects of the U.S. high-energy physics program.

The Snowmass Theory Frontier recommends vigorous support for a broad program of theoretical research as part of a balanced portfolio, augmented by targeted initiatives to connect theory to experiment; support and training for students and junior scientists; and strengthening the commitment to improve diversity, equity, inclusion, and accessibility. A general description of progress and promise in each of the three categories of theoretical high-energy physics research is given below.

(1) Fundamental theory: Fundamental theory (often also referred to as formal theory) seeks deep understanding of the theoretical and mathematical structures that underlie our modern description of Nature and includes directions that are not (or not yet) directly connected to experimentally testable consequences. The last century witnessed the triumph of quantum mechanics and classical relativistic gravity, both initially aspects of fundamental theory, whose impact on basic science and industry – and on our daily lives – have been enormous. Current research in fundamental theory explores the frameworks that arise at the intersection of relativity and quantum mechanics: quantum field theory and quantum gravity.

• **Quantum field theory:** The historical approach to the union of quantum mechanics and special relativity led to the successful formulation of quantum field theory (QFT). Our current understanding of high-energy experiments and cosmological observations is largely based on a perturbative approach to these theories. In the past decade, however, extraordinary progress has been made in developing new non-perturbative approaches to quantum field theory (including the advent of diverse bootstrap methods); extending the reach of perturbative computations (particularly for scattering amplitudes); and more fully leveraging effective field theory descriptions of physical systems. This progress has been made in tandem with complementary advances in lattice field theory quantifying non-perturbative properties in theories of interest. A new understanding of symmetries (including higher form symmetries, higher group symmetries, sub-system symmetries, and non-invertible symmetries) has also played a role in this progress. Although such generalized symmetries have only been discovered quite recently, they appear to be abundantly realized in nature, with considerable relevance to both high energy and condensed matter physics. Finally, quantum information has provided an important new perspective on quantum field theory, in which entropy and entanglement play a prominent role. Using information content as the organizing principle has led to the recognition that the structure of entanglement sheds new light on the properties of QFTs.

• **Quantum gravity:** The union of general relativity and quantum mechanics remains one of the outstanding challenges of theoretical physics. Yet the greatest challenges have a tendency to catalyze the greatest progress. Fueled by a deeper understanding of holography and insights from quantum information, thought

experiments involving the quantum mechanics of black holes have had a transformative impact on our understanding of quantum gravity and the nature of spacetime. The emergent nature of spacetime implied by such considerations has been made concrete in string theory, where the AdS/CFT correspondence has shed light on the emergence of bulk gravitational spacetime from the field theory description on the boundary. Many open questions remain regarding the emergence of spacetime in the vicinity of black holes. Addressing these questions requires a deeper formulation of quantum gravity than we currently possess, comprising a clear goal for the coming decade.

• **Physics and mathematics:** From classical mechanics to general relativity, fundamental theories of physics have evolved hand-in-hand with mathematics. This is no less true for modern approaches to quantum field theory and quantum gravity. Recent implications for both geometric and algebraic aspects of mathematics have included direct connections between the classification of superconformal field theories and the theory of canonical singularities in algebraic geometry; wrapped brane states in string theory and the mathematics of enumerative invariants. Connections between QFT, string theory, and number theory are exemplified by the "moonshine program". Further relations between number theory, algebraic geometry, and quantum field theory are emerging from the geometric Langlands program. Recent work on perturbative scattering amplitudes also revealed deep connections to active areas of work in mathematics.

(2) Phenomenology: Particle phenomenology provides the connection between fundamental theory and the physical description of the real world, testable by experiments. Phenomenology helps to formulate the physics goals of particle experiments and identify promising new avenues for experiments. Phenomenology provides the tools to perform the precision calculations necessary to compare experimental results to theoretical predictions. Phenomenology also helps develop the methods used for successfully analyzing and interpreting the results of the experiments, and often identifies signals requiring novel analysis techniques.

• **Model building:** There are plenty of indications pointing to the need for BSM physics: the origin of neutrino masses, the quark and lepton flavor structure, the absence of CP violation in the strong sector, the coexistence of the weak and gravitational scales, and the origin of dark matter and dark energy responsible for the acceleration of the universe. Model building attempts to synthesize these clues into the next set of principles that determine the laws of physics at the shortest distance scales. While all BSM models of physics approximately reproduce the SM at low energies, they introduce a plethora of testable ideas using a broad range of theoretical approaches and techniques. Recent developments such as cosmological selection, neutral naturalness, and models of light dark matter have led to new experimental search strategies at existing experiments, as well as to formulations of wholly new experimental programs, often co-led by theorists.

• **Collider physics:** Collider phenomenology is an essential interface between the theoretical and experimental high-energy physics communities, serving various roles: from connecting formal investigations to experiments (such as providing guidance on the exploration of the physics possibilities), to supporting the experimental community with the essential tools to simulate and interpret data, to bringing information back to the theory community. An explosion of theoretical activity in collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.

• **Precision collider theory:** Theoretical techniques for precise experimental predictions are the backbone of a successful program in particle physics. They are necessary for the determination of the fundamental parameters of the SM to unprecedented precision and to probe beyond the SM to very short distances. Much progress has been made in recent years in increasing the accuracy of phenomenological computations, including perturbative calculations at higher orders, resummation of perturbative expansions, improved parton distribution functions, and Monte Carlo simulation packages and event generators. This topic is a prime example where cross-fertilization between phenomenology and fundamental theory has accelerated

progress in both areas. The discovery and characterization of the Higgs boson is a prominent example of the success associated with both collider phenomenology and precision collider physics.

• **Neutrino theory:** The discovery of nonzero neutrino masses requires new fundamental fields and new interactions. Theory played a central role in the development of the formalism of neutrino oscillations, including the solution to the twentieth-century solar and atmospheric neutrino puzzles. This role is expected to persist and evolve as the oscillation probes grow more sophisticated and diverse. The coming era of precision neutrino oscillation experiments promises precise measurements of fundamental neutrino mass and mixing parameters, providing important information on the nature of these particles. A theory-driven, coordinated program combining nuclear effective theory, lattice QCD, perturbative QCD, and event generation to quantify the multi-scale nuclear cross sections at the required level of precision has been launched, that will allow us to unlock the full potential of the present and future neutrino physics program. With their vastly disparate energy scales, observations of astrophysical and cosmological neutrinos provide a wealth of information that is complementary to terrestrial experiments, entwining astrophysics, cosmology, and particle physics phenomenology. Theory and phenomenology play a key role in using this information to deepen our understanding of neutrino properties and interactions.

• **Flavor physics:** The ongoing and planned quark and charged-lepton flavor experiments provide essential constraints and complementary information on BSM models. The richness of B physics and the large b-quark mass enable many complementary tests of the SM, and have been a driving force to develop new perturbative multi-loop and non-perturbative effective field theory techniques since the 1980s. Taking advantage of the large amount of experimental data and the growing number of precise lattice-QCD results for hadronic parameters, new techniques in flavor physics are now enabling advanced theoretical analyses to obtain constraints on promising BSM candidate theories, maximizing the discovery potential of the experiments.

• **Cosmology and astrophysics:** Cosmology and astrophysics provide a wide range of opportunities to expand our knowledge of the fundamental laws of nature, both through direct searches for BSM physics and through tests of the SM in extreme conditions that are impossible to recreate in the laboratory. The impact of theoretical effort in cosmology and astrophysics over the past decade includes advancing our understanding of fundamental physics by forcing us to ponder extreme scenarios where, e.g., quantum effects and gravity must be considered simultaneously; developing new microscopic models that can potentially explain the outstanding problems facing our understanding of nature; and inventing new approaches to test our best-motivated theories, in addition to developing the theoretical tools needed to properly interpret the resulting data. Considerable progress has been made in understanding inflation and properties of the early universe from the cosmic microwave background and large-scale structure. Dark matter theory is undergoing a renaissance with the exploration of the full range of allowed dark matter masses, numerous portals to dark sectors, and novel interaction mechanisms. Advances in dark matter phenomenology have gone hand in hand with new proposals for dark matter experiments, often envisioned and implemented by theorists. The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders.

• **Quantum Sensing:** The development of quantum sensing technologies has opened the door to new opportunities to search for new particles or interactions that arise in well-motivated BSM theories, enabling novel experiments, detectors, and measurements. Here high energy theorists are playing a central role in proposing and guiding such experiments in the pursuit of searches for new light-matter particles (axions, axion-like particles, dark photons, milli-charged particles), dark matter, gravitational waves over a large range of frequencies, and tests of quantum mechanics and of gravity – the list is long.

(3) Computational theory and quantum information: Computational theory seeks to quantitatively test our theoretical descriptions of physical phenomena and gain new insights into fundamental aspects of

the underlying theories, through developing and deploying computational methods. All areas of high energy theory benefit from or contribute to the development of computational methods to some extent. Computational theory is tied to enabling technologies, both driving and benefiting from ever more sophisticated and powerful platforms for classical computers, quantum computers, and quantum simulators, as well as algorithm development and code optimization.

• **Lattice QCD:** The development of computational methods for the study of lattice field theory was originally motivated by the desire to understand QCD in the non-perturbative regime. Since then, lattice QCD has been developed into a precision tool with applications to a broad range of observables. It plays a crucial role in interpreting experimental measurements in flavor physics yielding precise SM predictions that reveal surprising new tensions, while determinations of the strong coupling and the quark masses enable precision tests of the Higgs boson. The scope of lattice QCD is undergoing a rapid expansion, promising to provide quantitative access to important new observables in the coming decade, including, among others, PDFs, Transverse Momentum and Generalized Parton Distributions, multi-hadron systems, and inclusive scattering and decay rates, as well as observables involving nucleons and nuclei used in many low-energy searches for new physics.

• **Lattice Field Theory:** LFT provides access to non-perturbative properties of other QFTs with interesting strongly-coupled dynamics. Theoretical developments such as gradient flow RG and a novel lattice formulation of supersymmetric Yang-Mills are expected to yield valuable insights. Promising results have been obtained in studies of composite DM models and of emergent conformal symmetry in Yang-Mills theories with complex fermion content, among others.

• **Quantum Information:** Quantum computing and quantum simulation of QFTs hold great promise to overcome the limitations of Euclidean LFT for the study of systems such as real-time scattering dynamics and finite density systems. Recent dedicated efforts to develop the methods and theoretical foundations for quantum simulations of quantum field theories relevant to high energy theory are already yielding intriguing results on currently available hardware, offering great promise for computations of classically intractable problems in the decades to come.

• **Event Generators:** Event generators are vital for the success of experimental programs across all Frontiers, connecting experimental measurements to theoretical predictions by accounting for hadronization, initial and final-state evolution, and rescattering. State-of-the-art generators incorporate higher-order QCD and EW corrections, factorization theorems, parton evolution, and resummation of QCD and QED effects. Improvements to event generators (driven in part by modern machine learning methods) will lead to further reduction of systematic uncertainties, directly enabling future experimental success.

• **Machine Learning and Artificial Intelligence:** Machine Learning and Artificial Intelligence describe a broad class of learning algorithms, including e.g. deep learning architectures based on complex neural networks with many layers. Machine learning is now playing an increasingly important role in all areas of high energy theory, in particular, those that rely on theoretical simulations or numerical analysis. In event generators, all modules can be improved through ML, including phase space sampling, scattering amplitudes, loop integrals, parton showers, parton densities, and fragmentation. End-to-end ML generators, which use generative networks to directly generate parton-level events, complement standard generators in important ways. In LFT, ML applications are being developed for all stages of the computations, including the generation of gauge fields and correlation functions as well as the numerical analysis needed for the extraction of the physical observables. The development of novel machine learning methods based on new symmetry-preserving ML architectures for efficient sampling of gauge fields in LFT or of phase space in event generators is notable for its cross-disciplinary impact.

To summarize, as we enter an era with many promising experiments but few guarantees of discovery, theory is as important as ever. Theory unifies the Frontiers of particle physics. It is essential to the conception, execution, and interpretation of current experiments. Theory is an essential driver of the development and implementation of new, enabling technologies. It also extends well beyond by laying the foundations for future experiments and advancing our understanding of Nature in regimes that experiment has yet to reach. A robust theory program is vital to the success of current and future projects in particle physics.

1.4.10 Underground Facilities & Infrastructure Frontier [13]

Experiments that require low backgrounds from cosmic radiation often must be performed underground. Underground experiments address some of the most important topics in particle physics, including the search for dark matter; neutrino physics, including experiments using solar and atmospheric neutrinos and neutrinos produced by accelerators; neutrinoless double beta decay; cosmic-ray physics; supernova detection; and searches for proton decay. The physics underlying the program is varied and spans several Frontiers. For Snowmass 2021, each underground experiment is included in the frontier appropriate to the physics topic that it addresses and the availability of suitable underground space is considered by this Frontier.

The Underground Facilities and Infrastructure Frontier assessed the requirements of proposed and potential experiments for existing and planned underground facilities and compared them to the available underground lab space and characteristics worldwide to see whether the needs of the proposed program can be met. General needs for underground experiments include depth (overburden); space; availability of environmental radiation monitoring (muon, neutron, radon, Kr/Ar, etc.); muon and neutron veto: water or liquid scintillator; availability of calibration sources, including gaseous sources, neutrons; material screening capability; access for equipment and people; space for and availability of needed infrastructure (power, cooling, ventilation, etc) and local support, and underground machine shops.

Three important recommendations from Snowmass 2013/P5 2014 were to form a new international collaboration to carry out a world-class long-baseline neutrino experiment hosted by the U.S. using neutrinos produced at Fermilab and detected 1300 km ($\sim$ 820 miles) away at a depth of 1475 m (4850 feet) at the Sandord Underground Research Facility in South Dakota; perform a program of second generation (G2) dark matter experiments, and support on or more third-generation (G3) direct detection dark matter experiments. The first recommendation is now being realized by the LBNF/DUNE project and the excavation of the underground caverns (150 m in length $\times$ 20 m in width $\times$ 28 m height) for it is well along in South Dakota. The DOE Office of Science has participated in the construction of two G2 dark matter experiments, LZ, also at SURF in South Dakota, which has already reported world-class results, and SuperCDMS at SNOLAB in Canada, which will start taking data in 2023. The third of these recommendations, to embark on a G3 dark matter experiment, is only in its earliest stages of R&D and proposals for experiments. A G3 O(100-ton) detector will be required to fully explore the WIMP space. This and a suite of smaller (less expensive, and very innovative technologies) provide the best opportunities in the coming decade for a major discovery and resolution to the DM problem and are likely to need additional underground space.

Key conclusions from the Underground Frontier are:

UF Conclusion 1: Leverage the Long-Baseline Neutrino Facility excavation enterprise to increase underground space at SURF in a timely and cost-effective way to permit siting of next-generation underground high energy physics research experiments.

- Excavate and outfit one or more new underground caverns at SURF at the depth of 4850' to house at least one large next-generation experiment and some mid-size and small experiments.

UF Conclusion 2: Designate the Sanford Underground Research Facility as a U.S. Department of Energy User Facility.

UF Conclusion 3: Provide full support for the underground facilities hosting the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

UF Conclusion 4: Following the 2014 P5 Recommendation 20, R&D and decision making for a third-generation direct detection dark matter program should commence immediately to enable a construction start in the late 2020s.

UF Conclusion 5: To ensure a robust collection of scientific programs in underground facilities, support the enabling capabilities, technique development, and expertise required for underground experiments.

Taken together, these form a strategy and action plan for underground physics for the next decade and beyond.

The work of this Frontier is carried out by the following Topical Groups; UF01, Underground Facilities for Neutrinos; UF02, Underground Facilities for Cosmic Frontier; UF03, Underground Detectors (Absorbed into UF05); UF04, Supporting Capabilities; UF05, Synergistic Research; and UF06, An Integrated Strategy for Underground Facilities and Infrastructure. Key observations of the Topical Groups are:

Underground Facilities for Neutrinos and Cosmic Frontier The LBNF/DUNE program is the flagship U.S. high energy physics research program using accelerator neutrinos from Fermilab to study neutrino oscillations. Cavern space for both the Phase I and Phase II parts of the DUNE detector is being excavated now at SURF. Future neutrinoless double beta decay experiments supported by nuclear physics programs, possible next-generation dark matter experiments, and proposals for future large-scale detectors targeting measurements of neutrinos from natural sources (e.g., supernova, solar neutrinos, geoneutrinos, etc) are expected to require underground facility space and infrastructure in the coming decade and beyond. Multiple new underground dark matter experiments are being planned (at large, medium, and small scales). It remains an open question whether deeper experimental locations, e.g. 7400' at SURF, are required for future neutrinoless double beta decay experiments. New suitable spaces must be available by the late 2020s to meet the demand. This demand may be met in North America by a proposed new (beyond what is being done for DUNE) underground space at SURF or SNOLAB.

Supporting Capabilities and Synergistic Research Future, larger experiments will increasingly require underground assembly with stricter radioactivity requirements. There will need to be larger, cleaner clean rooms, often with better radon-reduction systems and increased monitoring capabilities for ambient contaminants. Methods to assay dust deposition and radon-daughter plate-out will need to be improved. There will be an increased need for underground machine shops. Additionally, many labs are considering adding underground copper electroforming to mitigate against cosmogenic activation, as has been successfully demonstrated at SURF. A survey was sent to all experiments that submitted white papers that used underground facilities asking them what their requirements were.

A survey of synergistic research in underground facilities showed such facilities are used by a range of communities including nuclear astrophysics, experiments probing fundamental symmetries, gravitational wave detection, and geology and geophysics. Interestingly, it appears quantum information science (QIS)—in particular quantum computing—may become a user of underground facilities. In all the cases identified, the synergistic research was either complementary or had dedicated facilities. In this way, no obvious conflicts between underground facility use for high energy physics and other research communities are predicted.

An Integrated Strategy for Underground Facilities and Infrastructure An important result of the work of this group is an updated list of existing and planned underground facilities, including their main

characteristics of interest to experiments, their availability for mid-sized and small experiments, the space and infrastructure available for large experiments, and any plans for new space. These summaries are given in the Frontier report. The existing facilities worldwide are found to be fully subscribed. Moreover, emergent applications have been identified beyond neutrino and dark matter searches, including quantum information science, quantum computing, and atom interferometry that can also benefit from underground operations and add to the demand for space. The Underground Frontier concluded that future experiments and programs and their enabling R&D require new space. They propose a possible addition of the underground space at a depth of 4850 feet at SURF in South Dakota and possible additional space there at a depth of 7400 feet. Possible locations, near the DUNE excavation, are shown in the report. These new caverns should be able to accommodate the next generation of underground experiments, which are estimated to need 25m x 25m x 25m. These new underground enclosures would open up space for new experiments and would provide the opportunity for SURF to host next-generation dark-matter or neutrinoless double beta decay experiments. These new underground spaces would position the U.S. to be a leader in underground physics.

From the properties and nature of the neutrino to the direct measurement of galactic halo dark matter, research performed at underground facilities tackles a collection of precision knowledge of the constituents of the Standard Model of particle physics to broadly open-ended search well beyond the Standard Model. In the Underground Frontier, we have identified the needs and requirements for underground facilities to continue to support the breadth of particle physics research planned in the coming 10–15 years.

1.4.11 Snowmass Early Career Report [14]

The Snowmass 2021 strategic planning process provided an essential opportunity for the U.S. High Energy Physics and Astroparticle community to come together and discuss upcoming physics goals and experiments. As this forward-looking perspective on the field often reaches far enough into the future to surpass the timescale of a single career, consideration of the next generation of physicists is crucial. The 2021 Snowmass Early Career (SEC) organization aimed to unite this group, with the purpose of educating the newest generation of physicists while informing the senior generation of their interests and opinions. The definition of early career used for this document is "people within 10 years of their most recent degree with time allowance for any long-term leave from the field". In practice, an overwhelming majority of the participants in the SEC group and those identifying with the term Early Career (EC) are at a graduate or post-graduate (e.g. postdoc) equivalent career stage.

One major activity of the SEC was the Snowmass Community Survey, which was designed by the SEC Survey Core Initiative team between April 2020 and June 2021 with the aim of collecting demographic, career, physics outlook, and workplace culture data on a large segment of the Snowmass community (both junior and senior). The team reviewed questions from past Snowmass surveys, developed new topics, and came to a consensus on the survey questions. The survey was released to the community on June 28, 2021, and had nearly 1500 total interactions before it closed on August 26, 2021. The survey questions broadly fall into seven categories: demographics, physics outlook, careers, workplace culture, diversity and racism, caregiving responsibilities, and the impacts of COVID-19. A high-level summary of the key findings and recommendations from the survey report can be found in the SEC contribution to this volume.

SEC organized a number of sessions at the Community Summer Study in Seattle, with a workshop-wide plenary that contained talks on the SEC core initiatives, survey reports, and long-term EC organizations across the High Energy Physics and Astroparticle community . Early career physicists took the lead in many other areas, including several successful events focused on industry careers, networking, and perspectives. They also hosted community discussions on mental health and invisible disabilities and were represented

in panel discussions on community topics such as COVID-19 and career development. The level of interest in the early career perspective for Snowmass and the future of SEC led to the scheduling of an additional feedback session on early career issues in the final days of the meeting. Various informal social gatherings also took place to connect early career scientists beyond professional capacities.

Additional recommendations from the SEC community given in the SEC contribution to this volume cover the areas of "Increasing Early Career Representation in Decision-Making Bodies", "Addressing Accessibility and Economic Equity", "Robust Equity, Diversity, and Inclusion", and "Empowering SEC for the next Snowmass Process".

1.5 Special Cross-cutting Topics

1.5.1 Prospects and Evaluation of Future Colliders

Extensive cross-frontier discussions and deliberations have taken place in the e^+e^- Collider (EF-IF-AF) and Muon Collider (EF-TF-AF) forums and in the collider Implementation Task Force (ITF). The outcomes of these activities are summarized below.

1.5.1.1 e^+e^- Colliders Forum [18]

The Snowmass 2021 e^+e^- Collider Forum discussions covered a broad range of future electron-positron colliders from e^+e^- Higgs factories - linear and circular - capable of providing a rich scientific program with sub-percent Higgs boson coupling measurements, to potential discovery machines for the next New Physics scales at O(10 TeV) center-of-mass energy. A circular Higgs Factory will provide the best precision for most Higgs couplings, but direct probing of Higgs self-coupling and ttH couplings is deferred to a future higher energy proton collider. By comparison, a linear Higgs Factory will provide access to the Higgs self-coupling and ttH coupling.

Key findings and recommendations of the Forum report [18], related to accelerators, include:

a) Higgs factories: primary consideration for the delivery of physics results is the start time of the physics program. Given the maturity of the technology, the ILC and the large storage rings hold the advantage of a possible early start of the program. The ILC and CEPC both discuss possible starts late in the 2030s. The FCC-ee would follow the HL-LHC program and start in the mid to late-2040s. C^3 discusses a start similar to that of ILC assuming the completion of a technology demonstrator. There is no published timeline for Fermilab-based collider options at this time.

b) FCC-ee and CEPC have a significant luminosity advantage and are able to complete the required runs at various luminosities faster but their larger civil engineering work requires significantly more time and cost. An early start of the civil engineering construction of a circular machine is therefore key to the timely realization of physics.

c) The ILC and C^3 have cost, energy-reach, and polarization advantages but with lower luminosity, needing significantly longer running time to achieve the same level of precision for measurements compared to circular machines. From a potential siting point of view, all but the C^3 and HELEN machines require greenfield sites.

d) Given the strong motivation and existence of proven technology to build an e^+e^- Higgs Factory in the next decade, the U.S. should participate in the construction of any facility that has a firm commitment to go forward. Awaiting such commitment, the U.S. should also pursue research and development of multiple options in this decade. This ensures that the global community will be able to begin constructing at least one such machine in the following decade. The potential siting of a facility in the U.S. should also be pursued.

e) Development of an O(10)-TeV scale e^+e^- machine based on wakefield acceleration with sufficient luminosity capability for O(10) ab^{-1} and energy-recovery technologies for improved power-to-luminosity costs, requires continued R&D investment. Corresponding accelerator R&D should focus on the development of self-consistent machine design parameters and the feasibility of attainment of collider specifications for the energy frontier.

f) In order to address the Detector R&D and preparation of a Technical Design an R&D program that goes beyond generic R&D is needed to address the specific challenges posed by the detector required for e^+e^- colliders. Such a program needs to start now for the technology to build a full-scale e^+e^- collider detector to be ready when the HL-LHC program is completed.

1.5.1.2 Muon Collider Forum: main findings and recommendations [19]

There has been a recent explosion of interest in muon colliders, as evident from a ten-fold increase in the number of related publications submitted to arXiv in the last couple of years. The topic generated a lot of excitement in Snowmass at meetings of the Energy, Theory, and Accelerator Frontiers and continues to attract a large number of supporters, including many from the early career community. The Muon Collider Forum invited many experts to give their perspectives and to educate the broader community about the physics potential and technical feasibility of muon colliders. It facilitated a strong bond and exchange of new ideas between the particle physics community and accelerator experts. Synergies with the Neutrino and Rare Processes Frontiers, as well as overlaps with nuclear science and industrial applications, were also extensively discussed. Finally, the Forum served as an interface between the U.S. community and the International Muon Collider Collaboration (IMCC) hosted by CERN.

Key findings and recommendations of the Muon Collider Forum report [19] include:

a) A multi-TeV muon collider offers a spectacular opportunity for the direct exploration of the energy frontier. Offering a combination of unprecedented energy collisions in a comparatively clean leptonic environment, a high-energy muon collider has the unique potential to provide both precision measurements and the highest energy reach in one machine that cannot be paralleled by any currently available technology. Not only does a $\geq$10 TeV muon collider provide a compact energy frontier machine, but also because at high energies emission of W and Z bosons from the initial state muon is enhanced, vector boson fusion becomes dominant. This is the reason why a muon collider is often also referred to as a "vector boson collider". The vector boson fusion channel provides the dominant production mechanism not only for single but also for multi-Higgs final states, and a novel exploration of the electroweak sector.

b) Given the LHC results, a 10+ TeV lepton collider going beyond the classic precision versus energy dichotomy is an ideal machine. The accelerator challenges of a multi-TeV Muon Collider are now considered to be overcome based on the technological advances achieved over the past decade. Significant progress has been made in the development of high-power targets and of high-field HTS solenoids, in the demonstration of the operation of normal-conducting RF cavities in magnetic fields, and in the self-consistent lattice designs of the various subsystems. No fundamental show-stoppers have been

identified. Nevertheless, engineering challenges exist in many aspects of the design, and targeted R&D is necessary in order to make further engineering and design progress.

c) There is an established plan and funding for muon collider-related R&D activities in Europe and it is imperative for Snowmass/P5 to reestablish R&D efforts in the U.S. and to enable participation of U.S. physicists in the International Muon Collider Collaboration (IMCC).

d) The most fruitful path forward toward the development of a conceptual design of a Muon Collider would be the engagement of the U.S. community in the IMCC. The U.S. Muon Collider community is well positioned to provide crucial contributions to physics studies, further advance the accelerator technology and detector instrumentation, and explore options for the domestic siting of a muon collider. An Integrated National Collider R&D Initiative discussed in Snowmass [20] can provide a much-needed platform for R&D funding for such accelerator and detector development.

e) Fermilab could be considered a candidate site for a Muon Collider with a center-of-mass energy reach at the desirable 10-TeV scale. The synergy with the existing/planned accelerator complex and neutrino physics program at FNAL is an additional stimulus for such an investment of effort. A set of Muon Collider design options, with potential siting at FNAL, could be a contribution to discussions at the IMCC and the international committees to eventually form a global consensus decision on siting and selection of the Muon Collider. Having a pre-CDR document summarizing the design for the FNAL-sited Muon Collider in time for the next Snowmass is a good goal. The preparation of such a document will require a substantial, yet affordable, investment. Such an investment will reinvigorate the U.S. high-energy collider community and enable much-needed global progress toward the next energy frontier.

f) Major advancements in collider detector technologies have the potential to dramatically reduce the impact of the challenges posed by beam-induced background (BIB). These technologies originate from HL-LHC detector upgrades and rely on precision timing and incorporation of particle flow into the tracking and calorimetry systems, among other techniques. Further improvements are certainly conceivable and should be explored.

1.5.1.3 Implementation Task Force (ITF) analysis [16]

The collider Implementation Task Force (ITF) was organized and charged with developing metrics and processes to facilitate a comparison between projects. The ITF comprises 15 world-renowned accelerator experts from Asia, Europe, and the U.S., members of the Snowmass Early Career, and the EF and TF liaisons. Corresponding metrics have been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron, and ep collider facilities, based on traditional and advanced acceleration technologies. An additional group consisted of versions of the proposals that could be located at FNAL. More than three dozen collider concepts have been comparatively evaluated by the ITF in terms of physics reach (impact), beam parameters, size, complexity, power, environment concerns, technical risk, technical readiness, validation and R&D required, cost, and schedule. The ITF report documents the metrics and processes and presents comparative evaluations of future colliders [16].

Table 1-2 is an excerpt from the ITF report Tables 1−5 and lists the main parameters along with four columns with a summary value for technical risk (years of pre-project R&D needed), technically limited schedule (years until first physics), project costs (2021 B$ without contingency and escalation), and environmental impact (the most important impact is the estimated operating electric power consumption). The significant uncertainty in these values was addressed by giving a range where appropriate. The years of required pre-project R&D is just one aspect of the technical risk, but it provides a relevant and comparable measure of

Proposal Name	c.m. energy [TeV]	Luminosity/IP 10^{34} cm^{-2} s^{-1}	Yrs. pre project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee$^{(1,2)}$	0.24	7.7 (28.9)	0-2	13-18	12-18	290
ILC$^{(3)}$-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC$^{(3)}$-0.38	0.38	2.3	0-2	13-18	7-12	110
C$^{3(3)}$	0.25	1.3	3-5	13-18	7-12	150
HELEN$^{(3)}$	0.25	1.4	5-10	13-18	7-12	110
CLIC-3	3	5.9	3-5	19-24	18-30	$\sim$ 550
$\mu\mu$Collider$^{(1)}$-3	3	2.3(4.6)	>10	19-24	7-12	~230
FNAL$\mu\mu^{(1)}$	6-10	20(40)	>10	19-24	12-18	~300
FCC-hh$^{(1)}$	100	30(60)	>10	>25	30-50	~560

Table 1-2. *Main parameters of several collider proposals evaluated by the ITF: Higgs/EW factories, multi-TeV lepton collider proposals (3 TeV center of mass (COM) energy options), colliders with 10 TeV or higher parton COM energy (see the full list in [16]). The parenthetical superscripts next to the name of the proposal in the first column indicate (1) total peak luminosity for multiple IPs is given in parenthesis; (2) energy calibration possible to 100 keV accuracy for M_Z and 300 keV for M_W; (3) collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes. For each proposal, the ITF estimates are given on the years of pre-project R&D, years to first physics after the decision to proceed, construction cost (including explicit labor, no escalation, and no contingency), and facility electric power consumption.*

the maturity of a proposal and an estimate of how much R&D time is required before a proposal could be considered for a project start (CD0 in the U.S. system). Pre-project R&D includes both feasibility R&D, R&D to bring critical technologies to a technical readiness level (TRL) of $4-5$, as well as necessary R&D to reduce cost and electric power consumption. The extent of the cost and power consumption reduction R&D is not well defined and it was assumed that it can be accomplished in parallel with the other pre-project R&D. Nevertheless this R&D is likely most important for the realization of any of these proposals. (Note that by using the proponent-provided luminosity values, ITF chose not to evaluate the risk of failing to achieve this aspect of performance. However, performance risk was included in the evaluation of technical readiness in the ITF report.) The time to first physics in a technically limited schedule is most useful to compare the scientific relevance of the proposals. It includes the pre-project R&D, design, construction, and commissioning of the facility.

The total project cost follows the U.S. project accounting system but without escalation and contingency. Various parametric models were used by ITF to estimate this cost, including the cost estimated by the proponents. The cost estimate uses known costs of existing installations and reasonably expected costs for novel equipment. For future technologies, pre-project cost reduction R&D may further reduce the cost estimates used by the ITF.

Finally, the electric power consumption is for a fully operational facility including power consumption of all necessary utilities. The ITF used the information from the proponents if they provided it, otherwise, it made rough estimates based on expert judgment. Pre-project R&D to improve energy efficiency and develop more energy-efficient accelerator concepts, such as energy recovery technologies, have the potential to reduce electric power consumption significantly from the values listed in the tables.

Any of the future collider projects will constitute one of the largest − if not the largest − science facilities in particle physics. The cost, the required resources, and, maybe most importantly, the environmental impact in the form of large energy consumption will approach or exceed the limit of affordability. The ITF suggests

that the Snowmass 2021 final report recommends that R&D to reduce the cost and the energy consumption of future collider projects be given high priority.

1.5.2 Dark Matter Complementarity [15]

The fundamental nature of dark matter is a central theme of the Snowmass 2021 process, extending across all Frontiers. In the last decade, advances in detector technology, analysis techniques, and theoretical modeling have enabled a new generation of searches while broadening the types of candidates we can pursue. Over the next decade, there is great potential for discoveries that would transform our understanding of dark matter. A strong portfolio of experiments that **delves deep, searches wide, and harnesses the complementarity between techniques** is key to tackling this complicated problem, requiring expertise, results, and planning from all Frontiers of the Snowmass 2021 process. In a cross-cutting contribution to the Snowmass process, participants across Frontiers collaborated to outline a road map for dark matter discovery.

Complementarity drives discovery in multiple ways. The space of viable DM candidates and their properties is large, and a single experimental approach cannot test all the possibilities; a diverse range of techniques provides access to a much broader ensemble of DM scenarios and properties. Different approaches offer unique discovery sensitivity to distinct scenarios and regions of parameter space, and results from any one class of searches can continuously inform the interpretation of other measurements. Lastly, different DM experiments can be co-located and/or profit from the same or similar technological infrastructure. Each of these facets of complementarity is illustrated in the DM Complementarity Report through summaries of the efforts across all Frontiers and four case studies of models generating significant interest in the Snowmass process: minimal WIMP DM, BSM and vector portal DM, sterile neutrino DM, and wave-like DM including QCD axions.

The DM Complementarity Report proposes the following strategy for discovering the fundamental nature of DM:

Experiments at all scales are needed to cover the broad range of theoretically motivated parameter space. Existing and planned large-scale facilities across the HEP Frontiers have exceptional potential to discover fundamental properties of DM. We should commit to scaling up mature technologies that can promise significant sensitivity improvements, maturing potentially transformative new technologies, and supporting efforts to maximize and make accessible large projects' science output in the search for DM. We should support DM opportunities at multi-purpose experiments, including cosmology experiments, from the design stage through analysis. At smaller scales, execution of the existing Dark Matter New Initiatives (DMNI) program and similar future calls are necessary to build the most compelling portfolio of DM experiments, develop experience in project execution, and accelerate the pace of discovery.

Understanding the fundamental nature of DM is a worldwide endeavor. Coordination and cooperation across borders are critical for discovery. While building a strong U.S.-based program, we should pursue opportunities to leverage key U.S. expertise as a collaborative partner in international projects and play a leadership role in this major discovery area.

A strong theory program is essential to make connections between experimental Frontiers and take full advantage of new developments in simulation and analysis techniques. Theorists' input has been and will be critical for developing innovative new approaches to better understand and detect DM, and for determining how to predict and relate signals across a range of experimental probes.

Searches for DM benefit from cross-disciplinary expertise, with examples ranging from nuclear physics to metrology, and astrophysics to condensed matter and atomic physics. Mechanisms to support such interdisciplinary collaborations should be established.

Research funding is critical to enable discovery and build on new capabilities, across all Frontiers and project scales, in projects focused specifically on DM and to support DM analyses at multi-purpose experiments. The number of active efforts exploring DM has increased tremendously in the past decade, without a concomitant increase in research funding. Without such support, the community will not be able to execute the complementary dark matter program, decreasing the chances of solving the mystery of DM.

DM presents a fundamental puzzle to particle physics. To make progress on this challenging problem, maximize the chances of a transformative discovery, and fully elucidate the properties of DM and related new physics in the event of such a discovery, we advocate for a cross-frontier effort incorporating multiple complementary approaches to the problem. A decade of coherent cross-frontier DM exploration is an opportunity that should not be missed.

1.5.3 Synergies and Complementarities with Astrophysics and Nuclear Physics

Particle physics has very significant synergies with related fields of science, most notably nuclear physics and astrophysics. The practical and intellectual synergies between particle physics, astronomy, astrophysics, astroparticle physics, and cosmology have been growing exponentially since the early critical discoveries in cosmic rays: the existence of the positron, observed in cosmic ray emulsions in 1932 and quickly recognized to be the anti-particle of the electron required by the Dirac equation; the totally unexpected discovery of the muon in 1936 – just the tip of the iceberg of flavor; in 1947, the completely surprising discovery of mesons ushered in hadron physics which, now in retrospect, provided the first hint of QCD's quark substructure. Experimental particle and nuclear physics emerged together, going back to Lawrence's invention of the cyclotron. Cosmology and General Relativity became real experimental sciences with the discovery of Cosmic Microwave Background radiation (using instrumentation developed by physicists).

These seeds matured into new branches of physics: particle physics, astrophysics, and nuclear physics focused on related but distinct topics over the years. Nonetheless, important areas of overlap remain. Many scientists work on the interface between these fields and indeed participate in scientific endeavors led by several communities. There is also significant complementarity and common development of experimental and theoretical tools, instrumentation, and computational and analysis techniques. The issues of workforce development, equity, inclusion, diversity, and community engagement are also common among these fields and warrant common approaches.

Theoretical approaches in particle, nuclear, astrophysics, and cosmology are highly complementary. The fields start from the same fundamental Lagrangian and deploy common tools and techniques. Effective Field Theory – developed into a powerful tool within particle theory – is now a standard part of the toolkit for nuclear physics; recently, the application of the EFT technique has significantly increased the sensitivity of analyses of cosmological data. AdS/CFT, once the domain of formal particle theory, has produced a lower bound for the shear viscosity of the quark-gluon plasma that is in fact saturated in heavy-ion collisions. Advanced computational techniques such as AI and lattice gauge theory are other shared examples. Contributions from several fields are often needed to properly interpret observations. For instance, predictions of the neutron star mass-radius relation and other observables depend on both the equation of state at the cores of neutron stars, pushing the boundaries of our understanding of QCD, and on the properties of the nuclear neutron skin, which rely on nuclear theory and are verified by precision measurements of parity violation in electron scattering off heavy nuclei; models of exploding supernova

with verifiable predictions rely on measurements of nuclear reaction rates and properties of the neutrinos. The standard cosmological model is sensitive to the number of active neutrinos and their masses. At the same time, understanding nuclear reactions and nuclear properties are becoming increasingly important for precision measurements in HEP, including the reconstruction of neutrino interactions at DUNE. Quantum computing is another area where both nuclear and particle physicists have overlapping interests, and where algorithms and computational techniques developed by one field can benefit the other.

As within the HEP program, experiments and projects in nuclear physics, astrophysics, astroparticle physics and observational cosmology benefit from joint developments of scientific instrumentation for particle detection, high-performance computing, and development of novel computational paradigms including AI/ML and quantum computing. Low-background experiments in HEP, NP, and astroparticle physics use shared underground space, and all these programs could benefit from or even require additional underground infrastructure going forward. The HEP program has the advantage of having a dedicated funding source for "blue-sky" Detector R&D, which has seeded and supported many novel developments before they could be deployed by specific programs and projects. Such R&D is crucial for the overall health and future prospects of all these fields. The coordinated development of novel technologies across fields and cooperation in their engineering and deployment would be broadly beneficial, and to other areas of science as well.

Two new initiatives that have direct support from the Office of Science through both the HEP and NP programs perhaps warrant special mention. The development of AI/ML techniques and algorithms and their application to domain sciences such as HEP and NP are one of the new congressional initiatives. HEP and NP scientists have already been actively developing these algorithms for decades, but new directions such as the deployment of AI to improve the efficiency and reliability of accelerator and detector systems, for automatic fault detection, and other similar approaches to complex systems could find industrial applications and potentially benefit the broad society. Astrophysics and cosmology also make powerful use of AI/ML in simulating and interpreting astrophysical and cosmological measurements. With limited funds available for AI/ML, it is important that our approaches are complementary, coordinated, and cohesive – instead of being competitive.

A second new congressional initiative with joint HEP-NP-Astro interest is Quantum Information Science. Quantum computing could one day lead to an exponential increase in performance, and allow us to tackle calculations that would otherwise be impossible. The development of algorithms that demonstrate a quantum advantage for HEP and NP is an important part of the program. Similarly, the development and deployment of quantum sensor technologies directly benefit measurements of CMB, gravitational waves, searches for dark matter, and rare processes such as $0\nu\beta\beta$ decay and EDMs. One should also point out that HEP and NP experiments also develop technologies that benefit QIS directly. Very large cryogenic installations require engineering solutions that are pioneered by our fields. The development of cryogenic electronics, in particular using industry-standard CMOS processes, is another area with direct QIS applications. And since nuclear physicists have demonstrated that the coherence time of superconducting qubits is affected by the presence of ionizing background radiation, low-radioactivity techniques, and deployment of underground installations, developed jointly by HEP and NP, are also becoming increasingly important.

Additional examples of the synergies and complementarities among HEP, Astronomy, Astrophysics, and Nuclear Physics are highlighted below.

1.5.3.1 High Energy Physics and Astrophysics

High Energy Physics research areas straddling the Particle-Astrophysics-Cosmology boundaries include dark matter, dark energy, and inflation, and the use of multiple cosmic probes (high-energy neutrinos, gammas, cosmic rays, and gravitational waves) and cosmological structure observations to constrain fundamental

particle physics. The discovery of neutrino mixing and hence mass emerged from anomalies in the solar neutrino flux relative to predictions of the standard solar model; now, cosmological limits on the sum of neutrino masses are more constraining of neutrino masses than direct measurements in particle and nuclear experiments. Early Universe Cosmology is a central part of particle physicists' toolbox for revealing physics beyond the SM, for instance, the limits on the existence of not-yet-discovered light particles from the observed abundances of primordial nuclei and other cosmological probes are superb complements to accelerator studies. An emerging very important input for understanding QCD and nuclear physics are the discoveries of neutron stars with masses distinctly above $2M_{\odot}$ and breakthroughs in measuring the neutron star mass-radius relation by LIGO-Virgo with gravitational waves, and with NASA's X-ray telescope NICER; the results are challenging our understanding of QCD. The list goes on and on.

Reciprocally, particle physics gives invaluable contributions to Astrophysics and Cosmology. Two of the three themes prioritized by the 2020 Astro Decadal Survey are strongly aligned with the goals articulated in the Cosmic Frontier: "New Messengers and New Physics", with particular stress on multi-messenger astrophysics which will dramatically enhance the utility of cosmic particle and gravitational wave probes, as well as "Cosmic Ecosystems", aimed at improving our understanding of the astrophysical aspects of the evolution of the universe.

The underlying scientific motivation to study common topics is often different in the HEP and astrophysics communities, with astronomers interested for instance in questions like understanding the properties of galaxies and how they have evolved, and the menagerie of objects they contain, or the nature of the sources of the highest energy cosmic rays, whereas particle physicists are more focused on how the nature of the dark matter particle can be inferred from features imprinted on astrophysical systems, or distinguishing a potential dark matter annihilation signal from astrophysical background, or on using ultrahigh-energy cosmic particles to probe BSM physics far beyond accelerator energies. Since an essential part of discovering new phenomena through astrophysics and cosmology is understanding the baseline expectations of the standard model of cosmology and the many other aspects of astrophysics that produce foregrounds and backgrounds to some possible BSM signal, physicists and astrophysicists have a common purpose in these explorations.

Technologically, there is also a strong synergy between particle physics and astrophysics. A major triumph of the past decade in astrophysics was the discovery of gravitational waves by Advanced LIGO, largely funded by the NSF, which made essential use of developments spearheaded by HEP in vacuum systems, alignment challenges, distributed control, and data acquisition systems. A proposed future much larger gravitational wave observatory would further benefit from HEP expertise in km-scale facility placement, design, and execution, as well as the operation of multi-billion-dollar facilities. The scientific rewards of such an instrument for particle physics span from an independent, accurate measurement of the Hubble constant, to the determination of the QCD equation of state in neutron stars, to strong constraints on theories of modified gravity, to signatures of phase transitions in the Early Universe, and much more. Another triumph has been the detection of ultra-high-energy astrophysical neutrinos with the IceCube detector at the South Pole.

Presently coming to fruition, the Rubin Observatory was the highest priority ground-based project of the 2010 Astro Decadal survey. Among its goals are mapping the structure of the Universe and its expansion history in much greater detail and precision than at present, which is of key importance for particle physics because of what it can tell us about inflation and dark energy, and possible tensions within ΛCDM - as well as a multitude of applications in high energy and other parts of astrophysics. Its remarkable camera, LSSTCam, has been built at SLAC with DOE funding and expertise. LSSTCam presented a number of technical challenges that had not been encountered with other astronomical cameras: large modular arrays of 4-side buttable detectors with extremely tight positional tolerances; fast readout necessitating a high degree of parallelization with several thousand channels of readout electronics; finally, the positioning of the camera within the beam exiting the secondary mirror implied a severely constrained envelope to work in,

with tight thermal requirements. These features are more characteristic of the inner detectors associated with collider experiments than they are of typical ground-based astronomical instrumentation. The team assembled to design and build the camera (largely at SLAC, BNL, and the IN2P3 labs in France) mostly involved technical people from the HEP community who had experience with such issues.

A current example of astro-EPP technical synergy is in building CMB-S4, one of the key projects identified by the last P5, which will have unprecedented sensitivity to the physics of the Early Universe. The CMB-S4 transition-edge-sensor bolometric detectors, the superconducting circuity to make them dual-polarization and dual-band sensitive, and the low-noise SQUID-based multiplexed readout were all advanced by DOE-funded research. The laboratories involved include SLAC, LBNL, ANL, and FNAL. Another crucial HEP contribution has been the capability of LBNL NERSC computing to support the large data sets and the computation of the large sets of simulations needed to properly conduct the analysis.

These examples hardly scratch the surface of the multitude of ways that prior and current investments in particle physics R&D provide tools and expertise for astrophysics and other areas of science.

1.5.3.2 High Energy Physics and Nuclear Physics

The Nuclear Physics community is currently developing a new Long Range Plan (LRP) for Nuclear Science, aimed to be released in 2023. The fact that it coincides with the Snowmass and P5 process is an opportunity to further develop synergies, define common strategies when necessary, and maximize the scientific and societal impact of both fields.

Heavy ion measurements at the LHC are performed with the ATLAS and CMS detectors, as well as a dedicated detector ALICE. This complementarity and collaboration between the scientists working on high-energy colliders will grow with the advent of the Electron-Ion Collider (EIC). EIC, the top priority new facility construction in the 2015 Long Range Plan for Nuclear Science, will be the premier facility for precision studies of nuclear and nucleon structure, including the polarization and angular momentum observables, and the transition between the perturbative and non-perturbative regimes of QCD. The fundamental interest in the understanding of quantum chromodynamics at all regimes is a common thread between HEP and NP. Precision studies of the QCD, measurements of the parton distribution functions with high precision, and computational techniques that would be tested by the EIC could inform future measurements at the Energy Frontier. Conversely, nuclear collider experiments, including at RHIC and at the EIC, benefit from the tools and techniques developed by HEP, in particular jet reconstruction, precision tracking, heavy flavor tagging and reconstruction, calorimetry, particle ID, and others.

The overlap of scientific interest between nuclear and high-energy physics is probably greatest in the Neutrino Frontier. Snowmass has discussed in detail the many overlapping interests of neutrino scientists, and the desire of the scientific community to find ways to enhance the collaboration in neutrino physics while respecting the specific interests of the various stakeholders. The most pressing questions – the fundamental nature of the neutrino and the violation (or conservation) of lepton number, the number of neutrino species, the absolute scale of the neutrino mass and its fundamental electromagnetic properties, as well as precision studies of the ways neutrinos interact with matter – are of great interest to both communities. In fact, studies of neutrino oscillations are performed by both communities and supported by both OHEP and ONP, depending on the neutrino sources; some experiments, including SNO and KamLAND, have been supported by both OHEP and ONP. These are just a few examples of constructive and fruitful collaboration between the two fields.

Neutrinoless double beta ($0\nu\beta\beta$) decay remains an important topic for both HEP and NP. The next-generation ("ton-scale") experiments will be stewarded by the Office of Nuclear Physics, as recommended

by the 2015 LRP. It is also well recognized by the community and the funding agencies that the quest for, or perhaps precision measurements of, $0\nu\beta\beta$ decay must continue beyond these experiments, independently of whether the discovery is made at the ton scale. The Snowmass process has showcased a plethora of novel ideas and experimental techniques aimed at developing experiments with sensitivity beyond the parameter space defined by the inverted ordering of light neutrino masses. At this scale, it would be especially important to develop multi-purpose detectors and maximize the scientific return on investment. Synergies in technologies between $0\nu\beta\beta$ and dark matter experiments, $0\nu\beta\beta$ and CEνNS experiments, as well as $0\nu\beta\beta$ and the long-baseline neutrino program, were discussed at Snowmass. Deployment of such multi-purpose detectors may require cooperation between multiple communities and funding agencies.

Measurements of other neutrino properties such as the absolute neutrino mass or the neutrino magnetic moment, and new technological developments that could be pursued by both fields to enhance sensitivity, have also been discussed at Snowmass. Searches for sterile neutrinos – with different sources and detection techniques but in overlapping parameter space – are done by both HEP and NP. Measurements of neutrino cross sections, and of other processes that could improve the precision of neutrino reconstruction at DUNE, are examples where NP experiments could provide crucial input to a flagship HEP program. Examples of such HEP/NP collaborative experiments include electron-nucleus scattering experiments at Jefferson Lab, as well as neutrino scattering experiments at Oak Ridge National Laboratory's Spallation Neutron Source (a DOE Basic Energy Sciences facility), which produces very high-quality, high-intensity neutrinos.

Precision tests of the Standard Model is another area where nuclear and high energy physicists complement each other, and in some cases directly collaborate. The Muon $g-2$ experiment is a great example of a project funded primarily by HEP and operated at a HEP facility in which NP-funded scientists played a crucial role, brought specific expertise, and made substantial contributions. Precision measurements of electroweak couplings of electrons and quarks through parity-violating electron scattering at Jefferson Lab and at the EIC will provide an important window to search for new physics and will complement electroweak observables at the LHC and at the Z pole. Measurements of the CKM parameters, in particular those connected to the first generation, are often done in nuclear processes and are of great significance for the tests of the unitarity of the CKM matrix. Searches for Lepton Number and Baryon Number violation, EDMs, tests of lepton universality, and searches for dark sector bosons are other areas of joint interest. Some of the experiments with HEP funding are performed at NP-funded facilities (e.g. dark sector searches at Jefferson Lab) and therefore require collaboration between the offices. Searches for EDMs, enhanced by the advent of new atomic techniques and the use of molecules and deformed, often unstable, nuclei could be performed at nuclear facilities, such as FRIB. Conversely, the Advanced Muon Facility proposed at Fermilab could enable measurements that would benefit nuclear physics experiments directly, e.g. through precision measurements of muon capture.

The U.S. Nuclear Physics community (in particular the DOE Office of Nuclear Physics) operates multiple accelerator facilities. Among the larger ones are the Relativistic Heavy Ion Collider (RHIC) at BNL, the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab, the Facility for Rare Isotope Beams (FRIB) at Michigan State University, and a score of smaller accelerator facilities at national labs and universities. The highest priority for new facility construction in the 2015 LRP is the Electron-Ion Collider (EIC), to be built and operated at BNL by the beginning of the next decade. This facility is the only particle collider expected to be operated in the U.S. in the 2030s. It will require significant innovations in accelerator physics and technology and will employ a substantial fraction of the accelerator physics workforce in the U.S. The developments stimulated by HEP – high-field magnets, accelerating structures, power delivery systems, polarized sources, final focus systems, beam instrumentation, and precision control of the beam dynamics – will be deployed, further developed, and thoroughly tested by the EIC project. EIC will play an essential role in recruiting, training, and supporting the future accelerator frontier workforce. This workforce will be essential for any U.S. involvement in future large-scale accelerator projects for HEP and other fields.

1.6 Summary

The aspirations of the U.S. HEP community as informed by the Snowmass 2021 process can be succinctly summarized as follows:

> *Lead the exploration of the fundamental nature of matter, energy, space and time, by using ground-breaking theoretical, observational, and experimental methods; developing state-of-the-art technology for fundamental science and for the benefit of society; training and employing a diverse and world-class workforce of physicists, engineers, technicians, and computer scientists from universities and laboratories across the nation; collaborating closely with our global partners and with colleagues in adjacent areas of science; and probing the boundaries of the Standard Model of particle physics to illuminate the exciting terrain beyond, and to address the deepest mysteries in the Universe.*

This volume presents the main conclusions of Snowmass 2021, whose goal was to examine the status and scientific goals of U.S. HEP and to propose essential scientific programs to pursue, and to thereby provide community input to the 2023 DOE/NSF "Particle Physics Project Prioritization Panel" (P5) charged with updating the strategic plan for U.S. HEP for the coming decade and beyond. The work included herein was the output of ten Snowmass Frontiers and their Topical Groups, which comprised a broad array of ground-breaking scientific research topics and the underlying technology and infrastructure needed to execute them, as well as a forum to examine how the U.S. HEP community can become more representative of and responsive to all members of our community and can engage with society as a whole.

The consensus of the Snowmass 2021 community was that the five science Drivers formulated by the 2014 P5 panel continue to be appropriate for the next decade. Specifically, the questions that should guide the planning for the next decade and beyond include:

1. Use the Higgs Boson as a Tool for Discovery,
2. Pursue the Physics Associated with Neutrino Mass,
3. Identify the New Physics of Dark Matter,
4. Understand Cosmic Acceleration: Dark Energy and Inflation,
5. Explore the Unknown: New Particles, Interactions, and Physical Principals.

As a result of the breadth of flavor physics, its potential for discovering BSM physics, and hints of possible new physics in the current data, the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a new science Driver: *flavor physics as a tool for discovery.*

For the future U.S. HEP experimental program, an important general conclusion of Snowmass was that the completion, construction, and operation of currently approved projects, especially those prioritized by P5 in 2014, such as the HL-LHC, LBNF/DUNE, LSST/Rubin Observatory, and Mu2e programs, is essential. Furthermore, as the construction of approved large experimental projects come to a completion, U.S. leadership in a broad and complementary set of new large experimental programs covering the general scientific areas of the Energy, Neutrino, Cosmic, and Rare Process and Precision Measurements Frontiers is needed to provide opportunities for incisive new discoveries. The specific projects considered are listed in section 1.2.1 of this document (without regard to cost or priority, since that is to be done by P5), and described in greater detail in the Frontier Reports in this volume as well as in the Topical Group Reports and

white paper references contained therein. In addition, the inclusion in the U.S. HEP experimental portfolio of a broad and complementary set of mid- and small-scale experiments is vital to maintaining the diversity of physics topics investigated and of timescales to completion that are essential for a vibrant program. Medium- and smaller-scale projects are discussed more fully in section 1.2.2 and in the reports in this volume.

A healthy HEP program requires more than projects, however, and the Snowmass community emphasized the need for robust support for physics research programs at universities and national laboratories. This consideration includes the strong and continued support for all aspects of particle theory, comprising the interconnected themes of fundamental theory, phenomenology, and computational theory. Also needed is greater support for the infrastructure and enabling technologies, namely accelerators, instrumentation and detectors, and computation — both targeted support for specific future projects and generic support to develop new enabling technologies.

Input received during the Snowmass process highlighted that HEP projects and research benefit from collaboration with adjacent scientific disciplines, such as Nuclear Physics, Astronomy and Astrophysics, Gravitational Physics, Atomic and Molecular Physics, Quantum Information Science and Sensing, and Materials Science, and contributes to them in return. Opportunities to strengthen and expand such collaborations are mutually beneficial and should be pursued.

Of particular importance in considering the future of the U.S. HEP program is to understand and support the needs of its early career physicists. Snowmass participants recommended strengthening the connections between early career and senior researchers, fostering the professional success of early career physicists both within and outside of academia, and ensuring that the voices of younger scientists are well-represented in physics and community planning.

Mindful of the continuing lack of diversity in particle physics, a strong consensus exists in the HEP community demanding the development of a cohesive, strategic approach to promoting diversity, equity, and inclusion in high-energy physics, in collaboration with funding agencies, universities, adjacent scientific disciplines, APS/DPF and others. Specifically, the community should institute a broad array of practices and programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision and to address the persistent under-representation of women scientists, LGBT+ scientists, scientists who are Black, Indigenous, and people of color (BIPOC), and scientists with disabilities.

The U.S. HEP community is generously supported by and embedded in the nation as a whole. The HEP community must therefore engage in a coordinated way with five other interrelated communities: academia, the K-postdoc education community, private industry, government policymakers, and broader society. Snowmass participants identified the need for a structure for formulating a coordinated approach to achieve these goals which is provided with the resources needed for success.

The Snowmass 2021 process highlighted the breadth, depth, and effectiveness of the U.S. HEP program in exploring the fundamental nature of matter, energy, space, and time. The remarkable progress that has been made in probing the boundaries of the Standard Model of particle physics since 2013 was analyzed, and different and complementary methods to move forward in uncovering the mysteries of nature were examined. Highlights and opportunities that were identified are described in detail in the reports in this volume, as well as in the numerous topical group reports and white papers summarizing the work done for Snowmass. The members of the U.S. high-energy physics community left the Seattle Community Summer Study workshop with an appreciation of the great opportunities present in each Frontier, the interconnections between the Frontiers, and the connections to programs in the rest of the world. Through the Snowmass process, the U.S. HEP community has created an integrated vision to make progress in the coming decades to advance our understanding of the Universe.

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2

Accelerator Frontier

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Executive Summary

For over half a century, high-energy accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity frontier research in high energy physics (HEP) continuously drive the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more power efficient. The increasing size, cost and timescale required for modern and future accelerator-based HEP projects arguably distinguish them as some of the most challenging scientific research endeavors and demand continuation of these efforts. In the meantime, the international accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals.

Major developments since the last Snowmass/HEPAP P5 strategic planning exercise in 2013-2014 include start of the PIP-II proton linac; construction for the LBNF/DUNE neutrino program in the US; emergence of a number of projects for Higgs/EW physics such as FCC-ee at CERN, CEPC in China and C^3 and HELEN in the US; a significant reduction of activity related to linear collider projects (ILC in Japan and CLIC at CERN); and paradoxically, the end of the Muon Accelerator Program in the US and creation of the International Muon Collider Collaboration (IMCC) in Europe. The last decade saw several notable planning advancements, including the US DOE GARD Roadmaps, European Strategy for Particle Physics and the Accelerator R&D Roadmap, EuPRAXIA, etc.

In addition, since the last Snowmass meeting that took place in 2013 was shortly after the confirmation of the Higgs, the goals for the Energy Frontier have changed as a result of the LHC measurements. While a Higgs/EW factory at 250 to 360 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or few TeV e^+e^- collider has diminished. Instead, the community is focused on a 10+ TeV (parton c.m.e) discovery collider that would follow the Higgs/EW Factory. This is an important change that will refocus some of the accelerator R&D programs.

The technical maturity of proposed facilities ranges from shovel-ready to those that are still largely conceptual. Over 100 contributed papers have been submitted to the *Accelerator Frontier* of the US particle physics decadal community planning exercise, *Snowmass'2021*. These papers cover a broad spectrum of topics: beam physics and accelerator education, accelerators for neutrinos, colliders for Electroweak/Higgs studies and multi-TeV energies, accelerators for *Physics Beyond Colliders* and rare processes, advanced accelerator concepts, and accelerator technology for Radio Frequency cavities (RF), magnets, targets, and sources.

In 2020-2022, extensive discussions and deliberations have taken place in corresponding topical working groups of the Snowmass Accelerator Frontier (AF) and in numerous joint meetings with other Frontiers, Snowmass-wide meetings, a series of Colloquium-style *Agoras*, cross-Frontier *Forums on muon and e^+e^- colliders* and the collider *Implementation Task Force (ITF)*. The outcomes of these activities are summarized below.

Future facilities: The accelerator community in the US and globally has a broad array of accelerator technologies and expertise that will be needed to design and construct any of the near-term HEP accelerator projects. P5 will need to prioritize what option(s) should be developed. **Planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process**. Accelerator experts can contribute to the US and international projects under consideration by providing top-down metrics for expected cost-scales and technology/timeline evaluations, following the ITF findings.

Among possible actively discussed future facilities options are:

- A multi-MW beam power upgrade of the Fermilab proton accelerator complex that seems to be the highest priority for the neutrino program in the 2030s; corresponding accelerator technology and beam physics studies are needed to identify the most cost- and power-efficient solutions that could be implemented in a timely fashion leading to breakthrough results of the DUNE neutrino program;
- Several beam facilities for axion and Dark Matter (DM) searches are shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAR (a 1 GeV, 100 kW PIP-II Accumulator Ring); in general, we should focus on more efficient utilization of existing and upcoming facilities to explore dedicated or parasitic opportunities for rare process measurements - examples are the SLAC SRF electron linac, MWs of proton beam power potentially available after construction of the PIP-II SRF linac, spigots of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC, etc;
- Possible future colliders - In addition to continuing support for the ILC that figured prominently in the last P5, there are several other approaches identified as both promising and potentially feasible, and call for further exploration and support: in the Higgs/EW sector - there is growing support for the FCC-ee at CERN and proposals of somewhat more advanced linear colliders in the US or elsewhere, such as C^3 and HELEN;
- At the energy frontier, discovery machines such as O(10 TeV c.m.e.) muon colliders have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these concepts could be explored technically and documented in pre-CDR level reports by the end of this decade.

The U.S. HEP accelerator R&D portfolio presently contains no collider-specific scope. This creates a gap in our knowledge-base and accelerator/technology capabilities. It also limits our national aspiration for a

leadership role in particle physics in that the US cannot lead or even contribute to proposals for accelerator-based HEP facilities. To address the gap, the community has proposed that the U.S. establish a **national integrated R&D program on future colliders** in the DOE Office of High Energy Physics (OHEP) to carry-out technology R&D and accelerator design for future collider concepts. This program would aim to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, IMCC). It would support the development of design reports on collider options by the time of the next Snowmass and P5 (2029–2030), particularly for options that can be hosted in the US, and the creation of R&D plans for the decades past 2030. **Without such a program there may be few accelerator-based proposals for a future P5 to evaluate.**

General Accelerator R&D: In addition to the above focused proposed activity, general accelerator technology development is critical and needs additional attention and support to achieve the community aspirations by the end of this decade:

- Novel high power targets should be developed to be able to accept multi-MW beams (up to 2.4 MW for the LBNF/DUNE Phase II, 4-8 MW for a future muon collider) - the task that requires dedicated high-power targetry R&D facility(ies); development of efficient high intensity, high brightness e^+ sources is critical for most Higgs/EW factory colliders;
- Energy-efficient SC and cold-NC RF cavities and structures need to demonstrate 70 MV/m and 70 to 150 MV/m gradients, respectively, which are needed for cost efficient compact Higgs factory linear colliders; also critical are exploration and testing of new materials with the potential of sustaining higher gradients and high Q_0 as well as development of efficient RF sources that could lead to significant cost reduction;
- Conceptual breakthroughs in 12-20 T high-field dipole magnets, $O(30$ T) solenoids and $O(1000$ T/s) fast ramping magnets should demonstrate convincing proof of feasibility for high energy proton-proton and muon colliders as well as other energy frontier collider schemes;
- Advanced wakefield accelerator concepts should strive toward demonstration of collider quality beams, efficient drivers and staging, and development of self-consistent parameter sets for potential colliders based on wakefield acceleration in plasma and structures (in close coordination with international programs such as the European Roadmap, EuPRAXIA, etc.);
- Finally, in accelerator and beam physics - the focus should be on experimental, computational and theoretical studies on acceleration and control of high intensity/high brightness beams, high performance computer modeling and AI/ML approaches, and design integration and optimization. The program should also include the overall energy efficiency of future facilities and re-establish a program of beam physics research on general collider-related topics towards future e^+e^- colliders and muon colliders.

The above items call for a substantial increase in accelerator R&D support. We suggest that corresponding discussions take place as part of the P5 deliberations and clearly formulate priorities that should be communicated to the OHEP and accelerator community. A series of follow-up workshops should update and formalize the U.S. strategic goals and roadmaps for each of the GARD thrusts. Education and workforce training for particle accelerators is of critical importance for several DOE SC offices (HEP, NP, BES, FES,...) and OHEP should take a lead in organizing discussions and formulation of a corresponding vision across the Office of Science and NSF. Additional measures are needed to make the US competitive in education and attraction of accelerator talent, such as:

- Strengthening and expansion of education and training programs, enhancement of recruiting, and promotion of the field (e.g., via colloquia at universities);

- Creating an undergraduate level recruiting program structured to draw in women and underrepresented minorities (URM) that could be coordinated with the USPAS, and corresponding efforts at all career stages to support, include and retain them in the field;
- Strengthen and expand capabilities of the US accelerator beam test facilities to maintain their competitiveness with respect to worldwide capabilities.

2.1 Introduction

For almost a century, high-energy particle accelerators have played a key role in shaping modern nuclear and particle physics. They also support forefront material science and biology research [1]. Some 140 large accelerators are in operation that support research and many are currently under construction – the High Luminosity LHC upgrade, PIP-II, NICA, XFELs, EIC, ESS, FAIR, etc – and will become operational in due time. We also see great progress toward future frontier facilities for neutrino and rare processes physics research, Higgs factories (linear or circular), and multi-TeV $pp, \mu\mu$ and e^+e^- colliders – all of which are in the focus of the Snowmass'21 discussions.

2.1.1 Snowmass process

Snowmass is a particle physics community study that takes place in the US every 7-9 years (the last one was in 2013). Snowmass'21 strives to define the most important questions for the field and to identify promising opportunities to address them, see https://snowmass21.org/. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Following in the footsteps of Snowmass, the HEPAP Particle Physics Project Prioritization Panel (P5) will take the scientific input from Snowmass'21 (final summaries to be available in September 2022) and by the Spring of 2023 develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.

2.1.2 2014 P5 recommendations

Previous P5 plans were developed in 2014 [2] and contained several recommendations related to accelerators, all of which have generally been addressed and implemented. Those include:

- *Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project* – the AUP-LHC project has started delivery of a few dozen large aperture high field Nb_3Sn IR quads for the HL-LHC; led by FNAL, BNL, and LBNL it is currently at the level of CD-3 and is on track to be completed by the LHC Long Shutdown 3 (LS3).
- *Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of*

collaboration if ILC proceeds. – significant effort on the ILC design, prototyping and testing culminated in a beam acceleration demonstration of the full ILC cryomodule with an acceleration gradient of 31.5 MV/m at the FNAL FAST facility [3].

- *Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of ≥1 MW by the time of first operation of the new long-baseline neutrino facility* – the 800 MeV H^- PIP-II SRF linac construction has started, the project aims to support 1.2 MW of proton power on the neutrino target for LBNF/DUNE, with first beam injection to the FNAL Booster in 2029; international contributions support some 30% of the project.

- *Recommendation 22: Complete the Mu2e and muon g-2 projects* – the FNAL accelerator complex has been modified to include Muon Campus machines and new beamlines that delivered 8 GeV protons on target to generate copious amounts of muons for the g-2 experiment, exceeding previous (BNL) statistics 12-fold; the proton beamline for the Mu2e experiment was commissioned in 2022.

- *Recommendation 25: Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.* – the US played a major part in the MICE ionization cooling experiment at RAL (UK) that successfully demonstrated $O(10\%)$ transverse emittance reduction (cooling) of 140 MeV/c muons [4]; the US MAP program was closed in 2016 just in time to witness creation of the CERN-led International Muon Collider Collaboration (IMCC) in Europe a few years later.

- *Recommendation 24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton- proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.* – many US accelerator experts have contributed to the design of the 100 TeV c.m.e FCChh collider [5]; a 14.5 T Nb_3Sn dipole has been developed by the US Magnet Development Program (MDP) and successfully tested in 2021 [6].

2.1.3 2015 GARD subpanel recommendations

Two remaining 2014 P5 recommendations – *Recommendation 23: Support the discipline of accelerator science through advanced accelerator facilities and through funding for university programs. Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities. Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.* – this recommendation was addressed by a follow-up HEPAP Accelerator R&D Subpanel in 2015 [7]. It was charged to identify the most promising accelerator research areas to support the advancement of HEP and recommended vigorous beam physics and accelerator research along five thrusts: accelerator and beam physics (ABP), RF acceleration technology (NC and SC RF), magnets and materials, advanced acceleration concepts (AAC), particle sources and targets.

The US OHEP supported these programs and corresponding facilities operations with a total of roughly 90M$ a year, distributed as estimated from FY19 as 36% for AAC, 22% for RF, 19% for materials and magnets, 15% for ABP, and less than 2% for targets and sources.

Most of the GARD thrusts have demonstrated impressive accomplishments since 2015, the most notable include (see more details below) construction and operation of the FACET-II User facility at SLAC (with unique 1nC, $1\times1\times1\mu$m 10 GeV electron bunches available to several hundred users), numerous breakthroughs at the BELLA laser-plasma Wake Field Accelerator (WFA) facility at LBNL (such as electron acceleration up to 8 GeV over a mere 0.2 m of plasma and a proof-of-principle 0.1 GeV + 0.1 GeV staging demonstration), construction of and start of beam physics research at the IOTA Ring at FNAL (with recent demonstration of Optical Stochastic Cooling of 100 MeV electrons), a functional 14.5 T Nb_3Sn magnet and 300 T/s HTS magnet prototypes and new advanced high-current density conductors employing artificial pinning centers; new surface processing techniques resulted in 35-55 MV/m gradients in SRF cavities with unprecedented quality factors (which have been successfully applied to the LCLS-II/HE project). The high power targetry research thrust is the only one among the approved GARD thrust areas that does not have a (very much needed) test facility yet.

2.1.4 Snowmass'21 Accelerator Frontier

The Snowmass'21 activities are managed along the lines of ten "Frontiers": Energy Frontier (EF), Neutrino Physics Frontier (NF), Rare Processes and Precision Frontier (RPF), Cosmic Frontier(CF), Theory Frontier (TF), Accelerator Frontier (AF), Instrumentation Frontier (IF), Computational Frontier (CompF), Underground Facilities (UF), and Community Engagement Frontier (CEF). The Snowmass Community Summer Study workshop took place in Seattle at the University of Washington on July 17-26 and represented the culmination of the various workshops and Town Hall meetings that took place during 2020, 2021, and 2022 as part of Snowmass'21. More than three thousand scientists have taken part in the Snowmass'21 discussions and about 1400 people participated in the Seattle workshop in person and remotely. In general, the international community was very well represented and many scientists from Europe and Asia participated as organizers of sessions and events, conveners of topical groups, and by submitting numerous Letters of Interest (short communications) or White Papers (extended input documents).

The key questions for the AF included:
What is needed to advance the physics?
What is currently available (state of the art) around the world?
What new accelerator facilities could be available in the next decade (or next next decade)?
What R&D would enable these future opportunities?
What are the time and cost scales of the R&D and associated test facilities, as well as the time and cost scale of the facilities?

There were 7 AF topical groups led by internationally recognized researchers: AF1 "Beam Physics and Accelerator Education" - Mei Bai (SLAC), Zhirong Huang (SLAC), Steve Lund (MSU); AF2 "Accelerators for Neutrinos" - John Galambos (ORNL), Bob Zwaska (FNAL), Gianluigi Arduini (CERN); AF3 "Accelerators for EW/Higgs" - Angeles Faus-Golfe (IN2P3), Georg Hoffstaetter (Cornell), Qing Qin (ESRF), Frank Zimmermann (CERN); AF4 "Multi-TeV Colliders" - Mark Palmer (BNL), Nadia Pastrone (INFN), Jingyu Tang (IHEP), Alexander Valishev (FNAL); AF5 "Accelerators for Physics Beyond Colliders and Rare Processes" - Mike Lamont (CERN), Richard Milner (MIT), Eric Prebys (UC Davis); AF6 "Advanced Accelerator Concepts" - Ralph Assmann (DESY), Cameron Geddes (LBNL), Mark Hogan (SLAC), Pietro Musumeci (UCLA); AF7 "Accelerator Technology - RF" Emilio Nanni (SLAC), Sergey Belomestnykh (FNAL), Hans Weise (DESY); "Magnets" - Susana Izquierdo Bermudez (CERN), Gianluca Sabbi (LBNL), Sasha Zlobin (FNAL); "Targets/Sources" - Charlotte Barbier (ORNL), Frederique Pellemoine (FNAL), Yin-E Sun (ANL).

More than 300 Letters of Interest and 116 White Papers were submitted to the Snowmass'21 AF topical groups. There were more than 30 topical workshops, 8 cross-Frontier *Agoras* (5 on various types of colliders: $e^+e^-/\gamma\gamma$, linear/circular, $\mu\mu$, pp, advanced concepts and 3 on experiments and accelerators for rare processes physics). Several special cross-Frontier groups were organized between AF,EF,TF,IF, and NF such as *the eeCollider Forum, the Muon Collider Forum, the Implementation Task Force* (see below), the 2.4MW proton power upgrade design group at FNAL, etc. All the AF LoIs, White Papers, links to all the workshops, topical group reports, the fora and the ITF report are available at the AF wiki page https://snowmass21.org/accelerator/start.

Below we present summaries on all the AF topics in three major categories: future facilities, accelerator R&D, and workforce education and training. Together with the above Executive Summary, they represent the Snowmass'21 Accelerator Frontier input to the Snowmass'21 final report and the 2023 P5 prioritization process.

2.2 Accelerator facilities for neutrino research (NF)

The leading accelerator-based facilities for high energy neutrino research are *superbeams* based on a conventional beam dump technique: an intense high energy proton beam is directed onto a thick nuclear target producing mostly pions and kaons that are captured by focusing magnetic horns in order to obtain a well directed beam of same charge secondaries. High-energy neutrino beams are products of the decays of charged pions and kaons in a long decay channel [8]. Superbeams sources operate with proton beam intensities close to the mechanical stability limit of the primary targets that is at present $O(1$ MW). The most powerful accelerators for neutrino research to date are the rapid cycling synchrotron facility J-PARC in Japan, that has reached 515 kW of 30 GeV proton beam power, and the Fermilab Main Injector delivering up to 893 kW of 120 GeV protons on target. These facilities support neutrino oscillation research programs at the SuperK experiment (295 km from J-PARC) and MINOS (810 km from Fermilab).

The needs of neutrino physics call for next generation, higher-power, megawatt and multi-MW-class superbeams facilities. Average proton beam power on the neutrino target scales with the beam energy E_b, number of particles per pulse N_{ppp} and cycle time T_{cycle} as $P_b = (E_b N_{ppp})/T_{cycle}$. Corresponding upgrades of the RF system and magnet power supply ramping rate $1/T_{cycle}$ have been initiated at J-PARC, while Fermilab has started construction of an 800 MeV SRF H^- PIP-II linac (Proton Improvement Plan-II) that will help to boost N_{ppp} and the Main Injector beam power to above 1.2 MW, and is considering further facility upgrades to get to 2.4 MW - see Fig.2-1.

Fermilab is now studying several accelerator approaches to further double that beam power to 2.4 MW to an enhanced DUNE experiment (as part of the LBFN/DUNE Phase II) that is presented as the highest priority for the neutrino program in the 2030s. Multiple options have been proposed including an additional high duty-factor linear accelerator, and either a synchrotron or storage ring for accumulation of intense beam current required for the experiments. Corresponding design studies are needed to identify the most cost- and power-efficient solutions.

Besides the J-PARC and FNAL accelerator complex upgrades, an additional high-power, long-baseline neutrino beam has also been proposed to use a 5MW beam from an upgraded ESS proton accelerator delivered to megaton-scale detectors to measure CP violation. The ESS neutrino Super Beam proposal is instructive in demonstrating some of the challenges, and perhaps ultimate limitations, of pushing to ever higher beam powers. The proton beam must be highly compressed so as to have a low duty factor – order of microsecond pulses, to be useful for experiments and be properly focused by pulsed horns. Linac-based beams, with their rather low peak current and high duty factor, must employ a ring to accumulate and

compress H^- beams to be useful in this way. The 2.5 GeV energy is on the low-end for high-power neutrino beams where pion production yield is marginally less efficient and particularly the proton flux on the target station is incredibly high, such that the target station must be split into four separate targets and focusing horns.

Other accelerator-based neutrino approaches are underway for other searches within neutrino physics. Several forms of "decay-at-rest" neutrino sources (often from high-power spallation neutron sources) have detected coherent neutrino interactions and offer potential approaches to sterile neutrino oscillations and dark sector searches. Additional opportunities exist in further exploiting the timing and kinematics of beams to gain additional experimental reach. Hadron colliders have been found to be significant sources of neutrinos and proposals are being developed to detect them at the LHC and future colliders. The neutrino factory concept (and its related proposals) remains an option for further precision in long- and short- baseline neutrino physics.

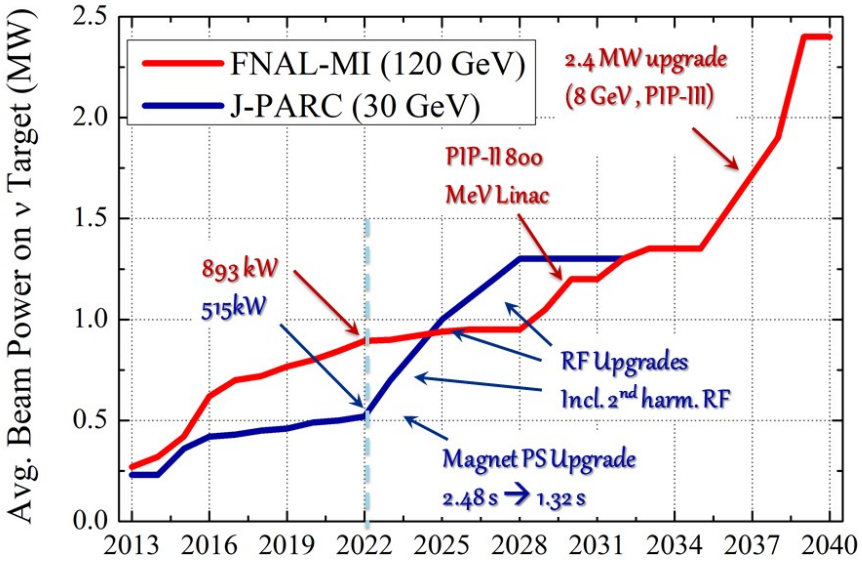

Figure 2-1. *Beam power progress and plans for J-PARC and the Fermilab Main Injector - two leading superbeam facilities for neutrino research (adapted from [8])*

2.2.1 Accelerators for Neutrinos: main findings and recommendations

The R&D needed for many of these next generation accelerators for the Neutrino Frontier vary widely - see the AF2 summary report [9]:

- Handling multi-megawatt beams proposed for future neutrino beams or for proton drivers for future muon colliders demand extremely robust targets able to withstand enormous thermal and mechanical stresses, ideally over long periods and with minimum maintenance.

- Superconducting proton linear accelerators have been a prominent tool to generate high power proton beams, but these beams must be compressed and formatted to short beam pulses that neutrino beam experiments require. Thus, development into higher-current linac H^- beams, H^- injection, and high-current accumulation are essential. Significant progress has been made in the design of alternative laser stripping schemes [SNS] but so far no operating high intensity machine is routinely using laser stripping for charge exchange injection and further research and development should be pursued.
- High current broadband or highly tunable RF is needed for synchrotrons and accumulator rings.
- Instabilities and loss control techniques are vital to all of the above machines as losses of $\ll 1\%$ can become prohibitive to operations, such that the machine's performance is limited more by efficiency than maximum current or energy. New concepts such as FFAs, integrable optics, space-charge compensation with electron lenses, and recirculating linear accelerators could provide advantages to future machines.
- Minimization of beam losses is critical to minimize damage to components and allow maintenance in case of failure. This requires the understanding of loss mechanisms and the implementation of these effects in simulation codes. The simulation effort should be accompanied by development of advanced diagnostics with high dynamic range to accurately characterize the beam properties to benchmark simulations and for protection and tuning purposes.
- Present and future high intensity circular machines such as FCC-ee and CEPC demand H^- low energy front-ends to maximize the beam brightness and minimize losses.
- Given the high beam power, maximization of the efficiency of future accelerators is mandatory to guarantee the sustainability and affordability of the research conducted with these machines in view of reducing the carbon footprint and contain the operation costs, particularly in the present international context of increasing energy prices.

2.3 Accelerator facilities for rare processes physics (RPF)

Many existing and planned high intensity accelerators can be effectively used for fixed target experiments complementary to high-energy-frontier colliders [10]. For example, a recent CERN study of the *Physics Beyond Colliders* (PBC) [11] resulted in numerous accelerator-based proposals, ranging from a gamma-factory [12] to explorations of the dark sector to precision measurements of either strongly interacting processes or light, feebly interacting particles at beam dump facilities, such as, e.g., the SHiP experiment [13] at the SPS North Area [14].

A similar study has been undertaken in the US as part of the Snowmass process. It considers a variety of potentially available beams ranging from 800 MeV to 120 GeV protons [15–17] to multi-GeV electrons [18]. Modifications of existing accelerator complexes and future dedicated scientific infrastructure should be considered for the next two decades through projects complementary to main stream applications of existing facilities. The main areas of interest include: a) low energy hidden sector searches for the QCD axion, and sub-eV Axion/ALP (helioscopes like, e.g., BabyIAXO/IAXO, haloscopes using resonant cavities (ADMX) or other methods (MADMAX), light-shining-through-walls experiments (e.g. JURA, STAX); b) Light Dark Matter searches in the MeV – GeV mass range target a parameter space of the Hidden Sector of special relevance to open questions in cosmology (proton beam dump experiments, e.g., BDF/SHiP NA62, MiniBooNE, SeaQuest; electron beam dump experiments NA64, LDMX, BDX, etc or novel use of existing facilities such as LCLS-II, CEBAF, FAST/IOTA, TRIUMF/ARIEL); or long lived particles at colliders (LHC, SuperKEKB); c) precision measurements and rare decays that can probe higher masses than accessible

with direct searches, via searches for the possible influence of the contribution of loop diagrams in a number of scenarios, e.g., ultra-rare or forbidden decays/reactions in the kaon sector - NA62, KOTO, KLEVER, lepton sector - TauFV, Mu3e, MEG,mu2e/mu2e-II, permanent EDM in protons/deuterons (CPEDM) or in strange/charmed baryons (LHC-FT), and the muon anomalous magnetic moment (g-2).

2.3.1 Accelerators for RPF: main findings and recommendations

Many of the above listed RPF initiatives can profit from ongoing advances in accelerator technology, e.g., high field superconducting magnets, superconducting RF, and are/could be considered at laboratories that host this technology and associated technical infrastructure. There was also significant overlap of AF2 discussions with other working groups within the Accelerator Frontier, specifically AF2 (Accelerators for Neutrinos) and AF7-T (Accelerator Technology - Targets and Sources).

Among the highest priorities in the AF5 "Accelerators for RPF" for the next decade are [19]:

- Optimum exploitation of the PIP-II Linac at Fermilab: The PIP-II 800 MeV proton SRF linac is currently set to provide only 17 kW of beam power for LBNF/DUNE, about 1.2% of the total potentially available beam of 1.6 MW. Individual experiments, like Mu2e-II, have come forward with fairly detailed proposals to use the 800 MeV beam directly from the PIP-II linac[2] but as yet **there is no coherent plan for beam distribution and beam usage**. Other muon experiments like $\mu \to e\gamma$ and $\mu \to 3e$ could also be carried out at this facility, although those proposals are not yet as developed. Although it is not high energy physics, a surface muon program has been proposed as well. To increase the sensitivity of the search for muon to electron conversion, an FFA has been suggested to produce a pure muon beam with a narrower energy and time spread.

- A new 0.8-1 GeV proton bunch compressor ring (PAR) has been proposed to accumulate beam from the PIP-II linac and extract it in intense bunches at rates of 100-1000 Hz. Such a compressor could serve not only Mu2e-II but also drive a set of dark sector searches based on beam dumps. Because of the relatively developed state of construction and planning for the PIP-II project, it is of priority to invest proper **effort into the design of the PAR and development of the experimental programs it can support.**

- Beam dumps support a broad range of experiments, generally searching for dark sector or other rare particles. These generally don't have demanding beam requirements beyond the total power and can use a wide range of beam energies of proton and electron beams, often almost parasitically. The competitiveness of any proposal in terms of physics reach and cost need to be carefully evaluated from a global perspective.

- Other opportunities and synergies: of particular interest is the Belle-II experiment at KEK, and storage rings for electric dipole moment measurements (e.g. electrostatic storage rings of the sort that have been proposed to measure the proton EDM). The BSM/RPF searches and activities are often synergistic with other R&D areas. These include overlaps in target development with ongoing R&D for neutrino or muon experiments, high field magnet development for "light through walls" experiments, and high-Q RF development that in this case is primarily for axion searches.

2.4 Colliders for Higgs/EW research (EF)

Charged particle colliders – arguably the most complex and advanced scientific instruments – have been at the forefront of scientific discoveries in high-energy and nuclear physics since the 1960s [20]. There are five electron-positron colliders in operation at present: DAΦNE in Frascati, Italy, VEPP-4M and VEPP-2000 in Novosibirsk, Russia, BEPC-II at IHEP, Bejing, and SuperKEKB at KEK, Japan. The SuperKEKB is an asymmetric e^+e^- B-factory with 4 and 7 GeV beam energies, respectively. Since the startup in 2018, SuperKEKB is pushing the frontiers of accelerator physics with crab-waist collisions, a world-record luminosity (for any collider type) of $4.7{\cdot}10^{34}$ cm^{-2}s^{-1}, and a vertical rms beam spot size of 300 nanometers. The future goal is $6{\cdot}10^{35}$ cm^{-2}s^{-1} (a whopping 30-times over its predecessor KEKB (1999-2010)), and a beam spot size of 50 nm. SuperKEKB is an important test-bed for FCC-ee and other future electron-positron colliders, and a key facility for training the next generation of accelerator physicists.

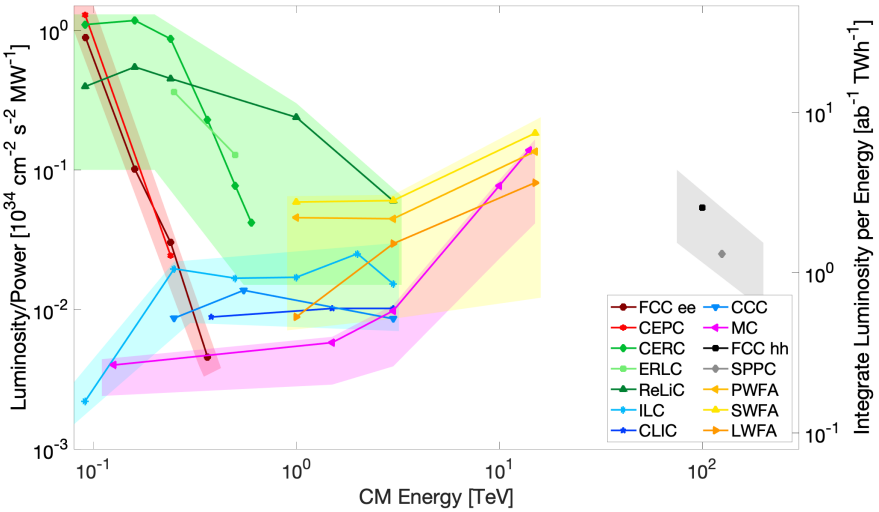

Figure 2-2. *Energy efficiency of present and future colliders. Luminosity per MW of the total facility power (left axis) and annual integrated luminosity per Terawatt-hour of electric power consumption (right axis) as a function of the centre-of-mass energy (from [21]). The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam.*

The world HEP community has called for a Higgs/EW factory as the next large accelerator project. At present, a dozen Higgs/ElectroWeak factory proposals are under consideration, including e^+e^- colliders such as the CEPC in China and FCC-ee at CERN, both on the order of 100 km circumference, that require O(100 MW) RF systems to sustain high luminosity [22]; or an 11 km long CLIC (CERN) two-beam normal-conducting RF linear accelerator with an average 72 MV/m gradient [23]; or the 21 km long International Linear Collider (ILC) based on SRF 31.5 MV/m SRF linacs [24]. Two recently proposed Higgs factories can potentially be shorter than 7 km and fit the Fermilab site - C^3 (employs 5.7 GHz 70 MV/m cool copper RF at 77 K) [25] and HELEN (1.3 GHz travelling wave SRF at 2K and 70 MV/m gradient) [26] - see Fig.2-3.

Besides technical feasibility and affordable cost, the most critical requirements for future particle colliders include the center-of-mass energy reach, the required AC site power consumption (see Fig.2-3), and the required duration and scale of the R&D effort to reach proper readiness – see detailed discussion in Refs. [20,21] and in Sec.2.7 below. Note that many of the future collider proposals have also been discussed in the course of the *2020 European Particle Physics Strategy Update* [27].

2.4.1 Proposed Higgs/EW physics facilities

Presented below are proposals for e^+e^- Higgs factories - colliders that operate at 240/250 GeV and, alternatively, also colliders with a staged program, including a stage above the top quark threshold. The latter colliders deliver superior physics performance for three reasons: (1) The top quark is another important object that needs precise study. (2) Above 350 GeV, the primary Higgs boson production mechanism changes from $e^+e^- \to ZH$ to WW fusion production of the Higgs. This capability is essential to prove the influence of beyond Standard Model physics on the Higgs boson. (3) Some measurements require data at two different, sufficiently well separated c.m. energies. The most important of these is the determination of the Higgs self-coupling from single Higgs production.

Most of the proposed Higgs/EW factories propose a significant run around the Z pole, opening a capacity for physics Beyond the Standard Model (BSM) through QCD and EW precision measurements. Analysis of the environmental footprint during construction and operation indicates significant differences among the Higgs/EW factory proposals [28].

International Linear Collider (ILC). The ILC is the most technologically mature of the proposed next-generation e^+e^- colliders - see [24]. The initial phase of the project has a c.m.e. of 250 GeV for precision studies of the Higgs boson, a major goal in collider physics. The ILC design assumes a high degree of polarization in both e^- and e^+ beams. As a linear machine it can operate at higher or lower energies. For example, the initial 21 km length can be extended to reach the threshold for the production of a top antitop quark pair ($t\bar{t}$) as well as for the associated production of a Higgs boson with a $t\bar{t}$ with c.m. energies up to 500 GeV with a length of 31 km. The site allows an upgrade to 1 TeV by extending the SRF linac lengths and, with improvements to the SRF cavities, c.m. energies of 3-4 TeV may be possible.

At 250 GeV, the primary enabling technology is Superconducting RF (SRF) cavities operating at an average gradient of 31.5 MV/m. The European X-ray Free Electron laser (XFEL) in Hamburg Germany is a multi-billion dollar project that provides a 10%-scale demonstration of the ILC acceleration systems with over 750 SRF cavities operating at an average of 23 MV/m and producing a 17.5 GeV electron beam for the XFEL. A Technical Design Report (TDR) for the ILC has been completed and the project is considered to be "shovel ready." At this point, the R&D focus is on reducing the cost of the cryomodules. The remaining technical challenges are: improvement of the positron source, achieving the nanometer-scale spot size and long-term stability and reproducibility at the interaction point (IP), and optimizing the damping ring injection and extraction systems.

The ILC would be the first truly global accelerator project. An International Development Team (IDT) was established by the International Committee for Future Accelerators (ICFA) in August 2020 to pave a way for the preparatory phase of the ILC. Hosted by KEK, it is intended to support the Japanese HEP community effort to host the ILC as a global project. It coordinates a continued effort in accelerator R&D for the engineering design. It also re-evaluates the ILC roadmap taking into account the global situation with an aim to trigger governmental discussion on the ILC as a global project that could lead to negotiations for the distribution of the cost and responsibilities for the construction and operation.

Compact Linear Collider (CLIC). The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider proposed by an international collaboration led by CERN - see [23]. The design is based on a staged approach that includes three c.m. energies of 380 GeV, 1.5 TeV and 3 TeV. In contrast to the ILC, CLIC uses a novel two-beam acceleration technique with normal-conducting accelerating structures operating in the range of 70 MV/m to 100 MV/m, and has only one beam polarized (e^-). A CDR was produced for CLIC in 2012 and, while the design is less mature than the ILC, the CLIC design parameters

are well understood and have been reproduced in beam tests indicating that the CLIC performance goals are achievable.

The main risks and uncertainties for CLIC will be in scaling from the small-scale low-power demonstrations to the km-scale high-power two-beam deceleration systems. Efforts to reduce power consumption are ongoing and new estimates show a significant reduction related to improvements in the X-band RF technology and klystron design. Like the ILC, other R&D includes improvement of the positron source, achieving the nanometer-scale spot size and long-term stability and reproducibility at the interaction point (IP), and optimizing the damping ring injection and extraction systems. In general, the spot sizes and stability requirements are tighter for CLIC than for the ILC while the positron system requirements may be easier due to a lower number of e^+/sec and a higher macro-pulse repetition rate that eases requirements on a rotating target.

Future Circular e^+e^- Collider (FCC-ee). The Future Circular Collider (FCC) is a proposed international collider complex located near Geneva Switzerland. It is based on the same successful staging strategy used for the Large Electron-Positron collider (LEP) and the Large Hadron Collider (LHC). The approximately 100 km tunnel would initially house the FCC-ee e^+e^- collider that would offer a broad physics reach operating at four different c.m. energies: the Z pole, WW threshold, the ZH production peak and the $t\bar{t}$ threshold. The tunnel could eventually house the FCC-hh, a 100 TeV proton-proton collider - see [29]. A Conceptual Design Report (CDR) for the FCC complex was completed and published in 2019 [30]; [5]; [31] and a Siting and Feasibility Study for the FCC-ee [32]; [33] will be completed in 2025, making it one of the more advanced proposals.

The main technologies for the FCC-ee are well-developed. The technology R&D is focused on incremental improvements aimed mainly at further optimizing electrical efficiency, obtaining the required diagnostic precision, and achieving the target performance in terms of beam current and luminosity. Optimization is also desired to improve the performance of the positron source, SRF and vacuum systems [34]. The FCC Feasibility Study, launched by the CERN Council in 2021, will address numerous key feasibility aspects, including tunnel construction, financing, sustainability and environmental impact. The result of the Feasibility Study will be an important input to the next European Strategy Update expected in 2026/27. The FCC technical schedule foresees the start of tunnel construction in the early 2030s, the first e^+e^- collisions at FCC-ee in the mid or late 2040s, and the first FCC-hh hadron collisions around the year 2070.

Circular Electron Positron Collider (CEPC). Proposed by Chinese scientists in 2012, the CEPC is an international scientific project hosted by China to build a 240 GeV circular e^+e^- collider in an approximately 100 km tunnel - see [22]. Similar to the FCC, the tunnel for the CEPC could eventually be used for a Super Proton Proton Collider (SPPC). A CDR for the CEPC was released in November 2018. The TDR is planned for completion at the end of 2022 followed by work on an Engineering Design Report (EDR) that will look at the detailed engineering design of components, site selection and preparations for industrialization.

Like the FCC-ee, the technological basis for the design is well-understood and the R&D focus is now on improving performance of the RF klystrons, SRF cavities, high precision magnets, and vacuum systems. The proposed schedule calls for first collisions in the mid-2030's.

Cool Copper Collider (C^3). The C^3 is a linear collider concept based on recent innovations in the technology of cold copper cavities providing power to each individual cell that allows for increased accelerator performance and better optimization - see [25]. Operation at liquid nitrogen temperature substantially increases the RF efficiency and gradient of normal-conducting copper cavities. For a 250 GeV c.m. energy the accelerator is 8 km and, with additional innovation in cost-efficient RF power sources, 550 GeV could be reached using the same footprint. A GeV-scale demonstration facility is proposed to provide input for a TDR. It would include three cryomodules operating at 70, 120 and 170 MV/m to test the RF design. A gradient of 155 MV/m

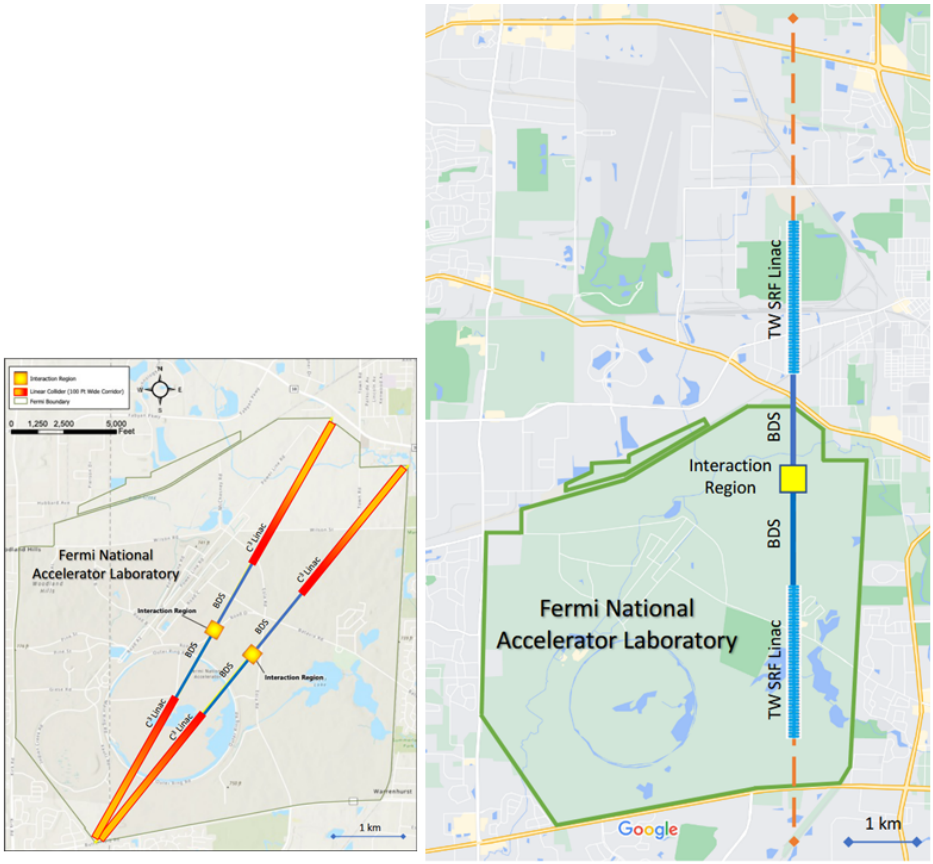

Figure 2-3. *Possible placements of future linear e^+e^- Higgs/EW factory colliders C^3 and HELEN on the Fermilab site map - both about the same length: (left) 250 GeV c.m.e. options with a 7-km footprint (from Ref. [26]), and (right) higher c.m. energy options (the orange dashed line indicates a 12-km stretch that might be made available for a future linear collider) [35].*

would be needed for the 550 GeV upgrade. Other collider subsystems can be based on those developed for CLIC and ILC. Areas of technical focus are development of an ultra-low emittance polarized electron gun that would benefit all linear collider designs, optimization of the RF structures and reducing the cost of the RF sources.

HELEN. The Higgs-Energy LEptoN (HELEN) linear e^+e^- collider proposal is based on advanced travelling wave (TW) 1.3 GHz superconducting radio frequency technology [35]. Relative to the ILC, the proposed collider offers cost and AC power savings, a smaller footprint ∼7.5 km (vs 20.5 km), and could be built at Fermilab with an Interaction Region within the FNAL site boundaries. After the initial physics run at 250 GeV c.m.e., the collider could be upgraded either to higher luminosity or to higher (up to 500 GeV) energies. The proponents' cost estimate for HELEN is about 15% less than the ILC-250 construction cost. If the ILC can not be realized in Japan in a timely fashion, the HELEN collider would be a viable option to build a Higgs factory in the U.S. All collider subsystems with the exception of the TW SRF can be copied from the ILC design. Corresponding R&D is needed to reduce technical cost risks, demonstrate the TW SRF cryomodules with 70 MV/m gradients and efficient e^+ generation - as for the ILC.

Energy Recovery and Recirculating Linacs (ERLs and RLAs). Linac-based and circular colliders with energy recovery are an alternative approach to high energy electron-positron colliders with the aim to significantly reduce beam energy losses and consequently, power consumption. There are two proposed configurations. A circular e^+e^- collider with two 100 km storage rings using Energy-Recovery Linacs (CERC) [36] [37] or two large linear colliders with damping rings, a Linear Energy Recovery Linac Collider (ReLiC) [38] and an ERL-based linear e^+e^- collider ERLC [39]. Starting as a Higgs factory they have the capability of achieving c.m. energies up to 600 GeV. The energy as well as the particles are recycled in this scheme and make fully polarized electron and positron beams possible. A large fraction of the energy of the used beams is recovered by decelerating them. The beams are then reinjected into a damping ring where they are cooled and reused. Beam that is lost during the recovery process is replaced via a linear injector into the damping rings.

ERL's are currently in a process of technological development. A number of compact ERL facilities and demonstrators have been constructed. The highest circulating Continuous Wave (CW) power was achieved in the IR FEL ERL at Jefferson Laboratory that operated with 8.5 mA at 150 MeV. A global development program for the ERL technology is discussed in [40].

X-ray Free Electron Laser Compton Collider (XCC). The XCC concept combines the cold copper distributed coupling technology of C^3 with X-ray FELs [41] to create a γ-γ collider. The linac accelerates electron bunches with a gradient of 70 MV/m until 31 GeV is reached, at which point alternate bunches are diverted to an X-ray FEL to produce circular polarized 1 keV X-rays using a helical undulator. The electron bunches remaining in the linac are accelerated to 62.8 GeV through a final focus system to the e^-e^- interaction points (IP). The 62.8 GeV electrons then collide with the focused X-ray laser light from the opposite X-ray FEL, producing 62.5 GeV photons that are then collided at 125 GeV c.m.e. in the primary IP. The number of Higgs' produced in such a machine would be comparable to the ILC, but backgrounds need to be studied in more detail.

Relative to some other e^+e^- Higgs factory proposals the XCC requires two additional beamlines and collision points and requires significant improvement to X-ray FEL technology. However, if a high brightness polarized RF gun can be developed, damping rings would not be required and the beam energy is half of that required for e^+e^- Higgs factories, raising the possibility of significant reduction in cost, a common obstacle for large-scale facilities. Gun development is challenging, but will benefit from experience with the LCLS-II-HE SRF gun when it turns on.

2.4.2 Higgs/EW Factories: main findings and recommendations

Comparisons of the main parameters of the proposed Higgs/EW factories were made for the linear colliders, the circular colliders and the $\gamma\gamma$ colliders. Critical R&D items were identified for each proposed collider, and consolidated R&D efforts that would jointly benefit several of the projects have been sketched out. Most of the proposed Higgs and Electroweak Factories can not be considered in isolation from other accelerators that are being proposed for higher energies. Higher energy machines would either greatly benefit from the infrastructure and accelerator developments described here, or would be a direct upgrade or extension of the Higgs and Electroweak Factory. This provides a natural connection to the accelerator topical group AF4 "Accelerators for Energy Frontier", see below in Sec.2.5.2.

Major conclusions of the AF3 group are [42]:

- Of all the Higgs/EW factory proposals considered, only a small number of them are ready or close to a construction phase - namely, the ILC, CLIC, FCC-ee and CEPC.
- Most of the other proposals are very high-level and in the conceptional design stage. These proposals should focus on the main R&D tasks to move forward to a TDR. A detailed estimation of the Technical Readiness Level (TRL) risk factor, technology validation, cost reduction impact, performance achievability and timescale to reduce the TRL are presented in detail in the Collider Implementation Task Force report [21] (see also, below in Sec. 2.7).
- The Higgs/EW factories centered on 240-250 GeV energy are not very challenging from the point of view of energy, but they are high-precision machines and luminosity will be the main figure of merit. Therefore, the focus of the R&D effort should be on how to make these colliders more compact, reducing the cost, and to assure the highest possible integrated luminosity within reasonable site power limits and duration of operation.

The joint technology research topics have been identified that will be most beneficial for all Higgs/EW facotory colliders:

- Energy: a) SRF: TW structures and Nb_3Sn (70 MV/m HELEN). Special concern has to be paid to the SRF for ERLs; b) NCRF: Cryo-cooled Copper structures (120 MV/m C^3), HTS coatings; c) cryogenics: mass industrial production, transport issues, gas-pressure regulations, more efficient gas coolers.
- Luminosity: a) positioning, monitoring, alignment and stabilisation: global strategies, instrumented girders, radiation-hard ground motion sensors; b) e^+ production optimization: flux concentrators, pulsed solenoid, capture linacs, targetry issues; c) nanobeam colliding techniques: concepts and feedback; d) damping rings and booster: low-emittance and 4th generation lattices for colliders; e) magnets: Interaction Region final focus systems and injection/extraction devices.
- Sustainability: a) Energy consumption, efficiency, carbon footprint; b) high-efficiency RF power sources: klystrons, solid state amplifiers and IOTs; c) permanent magnets.
- Other: a) manufacturing techniques including additive, cost reduction and mass production; b) high power beam dumps (multi-MW); c) machine protection and collimation; d) polarized beams and polarimetry; e) beam instrumentation; f) robotics and automatization.

The main technical topics to be worked on for individual proposals are:

- ILC: polarized e^+ production, final focus system (FFS), tunability and long term stability, FFS doublet vibration issues, Injection/extraction devices. For upgrades: SRF with higher Q, higher gradient, Traveling Wave SRF cavities, and Nb_3Sn.
- CLIC: mechanical vibration mitigation, cost efficiency, X-band components and RF sources. Cavities with partial HTS coating.
- C^3: RF optimized structure including cost reduction and industrialisation, cryomodule R&D, and an ultra-low emittance e^- source. Overall accelerator layout.
- HELEN: SRF with higher Q, higher gradient, Traveling Wave SRF cavities, and Nb_3Sn. Cryogenic optimization. Overall accelerator layout.
- ReLiC: SRF with higher Q, higher gradient, Traveling Wave SRF cavities, and Nb_3Sn. Cryogenics optimization. Test of high current, low loss energy recovery. Self-consistent and coherent parameter table and overall accelerator layout.
- ERLC: Dual-axis SRF cavities, higher Q, higher gradient. Cryogenics optimization. Test of high-current, low loss energy recovery. Self-consistent and coherent parameter table and overall accelerator layout.
- XCC: X-ray transport and focusing. Interaction-region layout with Compton collision point. FEL design. Overall accelerator layout and integration issues.
- FCC-ee: Single- and few- cell 400 MHz Nb/Cu cavities with high Q_0, two- and five-cell 800 MHz bulk Nb cavities; cryomodule design; efficient RF power sources at 400 and 800 MHz; efficient cryogenic system; "low-field" HTS magnet systems for the FCC-ee collider final focus, collider arcs, and for the positron source; magnet system for the fast ramping full-energy booster. High-field magnet systems based on Nb_3Sn and/or HTS in preparation of FCC-hh.
- CEPC: two-cell 650 MHz bulk Nb cavities; efficient RF power sources at 650 MHz and 1.3 GHz; cryogenic system; booster magnets. High-field magnet systems using iron based HTS for SPPC.
- CERC: SRF with higher Q, ultra-small emittance preservation, damping rings with very flat beams and large energy acceptance, use of small gap magnets for power and cost reduction. High repetition rate extraction and injection kickers. Self-consistent and coherent parameter table and overall accelerator layout.

2.5 Collider facilities for the energy frontier research with O(10 TeV/parton) c.m.e. (EF)

Currently, there are two operational high-energy hadron colliders - RHIC at BNL and LHC at CERN. The Large Hadron Collider now represents the "accelerator frontier" with its 6.8 TeV energy per beam, $2.1{\cdot}10^{34}$ $cm^{-2}s^{-1}$ luminosity and some 1 TWh of annual total site electric energy consumption. Since the start of operation in 2009, the LHC has delivered 190 fb^{-1}/IP in *pp* collisions – mostly over the past few years at 13 TeV c.m.e., exceeding its design luminosity goal by a factor of two. The High-Luminosity LHC upgrade will be completed by 2028 with the goal of reaching 250 fb^{-1}/yr at 14 TeV c.m.e. via doubling the beam current, lower beta-function at the IPs with new Nb_3Sn SC IR magnets, and using *beam crabbing* and *luminosity leveling* techniques [43]. The upgrade will be followed by a decade of operation to obtain a total integrated luminosity of 3-4 ab^{-1}.

Two colliders are under construction - and both will serve the nuclear physics research community - the NICA pp/ion-ion collider in Russia with $\sqrt{s}$=4-11 GeV with expected first collisions ca 2024 and the Electron-Ion Collider (EIC) in the US (BNL) that will collide 10-18 GeV electrons with ions/protons up to 275 GeV energies. The later will be an excellent test bed for HEP colliders. Many topics, including polarization, ERLs, cooling, etc. will be developed for this machine and will benefit future high energy colliders.

There are also about two dozen proposed energy frontier colliders that go beyond LHC in their discovery potential. Among them are the 3 TeV CLIC option (100 MV/m accelerating gradient, 50 km long), two roughly 100 km circumference *pp* colliders, the SPPC in China (75-125 TeV c.m.e., based on 12-20 T SC magnets) and FCC-hh at CERN (100 TeV, 16 T) [29], and a potentially more economical 10–14 TeV c.m.e. $\mu^+\mu^-$ collider (10–14 km circumference, 12-16 T magnets) [44]. R&D is in progress on other concepts such as wakefield based e^+e^- or $\gamma\gamma$ systems that may present additional future options.

2.5.1 Proposed energy frontier colliders

Future Circular Collider - hadron/hadron (FCC-hh). Proposed as a second phase of the FCC program after FCC-ee, the FCC-hh is a proton-proton collider aimed at increasing the physics reach by an order of magnitude beyond the LHC [45]. Following the same strategy used for LEP and LHC, the accelerators will utilize the same 100 km-scale tunnel. It is one of the relatively mature proposals, and a conceptual design report was published in 2019 [5]. One of the major enabling technologies are the 16 to 17 T superconducting magnets required to reach the target energy of 100 TeV. This field level does not currently exist, but programs in the US and EU/CERN are actively pursuing the R&D. Experience from the construction of high gradient quadrupoles for the LHC high luminosity (HL-LHC) upgrade will serve as a launching point for further development.

Attaining the desired luminosity of $30{\cdot}10^{34}$ cm^{-2}s^{-1} will be challenging. However, the HL-LHC will be an opportunity to gain considerable experience. Other challenges are related to the size and number of components, and increased number of injector rings, adding considerably to the overall complexity. Crab cavities, necessary for compensating the crossing angle at the interaction points, are still an untested system in hadron colliders, but the HL-LHC will provide an opportunity to develop this technology.

Super Proton-Proton Collider (SPPC). The SPPC is proposed as the second phase of the CEPC-SPPC, sharing the same tunnel in a scheme parallel to the FCC-ee/hh [46]. It is planned to operate at a c.m. energy of up to 125 TeV in the final stage using 20 T magnets with an intermediate stage at 75 TeV using 12 T magnets.

High-field magnets are the key enabling technology for future hadron colliders. A unique feature of the magnet technology proposed for the SPPC is the use of iron-based high temperature superconductor (IBS). This material is still in the early R&D stage, but if successful, has the potential for significant cost savings over currently available HTS materials. A few programs in the US and EU are also engaged in exploring the potential of IBS. The project is currently in the pre-CDR phase. In addition to the high field magnets, synchrotron radiation power, luminosity and site power are a consideration in the overall design [47].

Collider-In-the-Sea. The Collider-in-the-Sea is a 500 TeV c.m.e., 2100 km hadron-hadron collider to be located underwater in the Gulf of Mexico using low cost superferric SC magnets.

Muon Colliders. The muon collider has great potential to extend the energy of lepton colliders by taking advantage of the strong suppression of synchrotron radiation from muons relative to electrons, though the finite lifetime of the muon is a critical issue. This allows for efficient acceleration in rings and a more compact

RF system - see Fig.2-4 - as well as a better defined collision energy. For example, the energy consumption of a 10 TeV c.m. energy muon collider is estimated to be lower than CLIC at 3 TeV - see [44]. As a ring, a muon collider may be able to provide luminosity to two detectors.

There are a number of technological challenges that need to be addressed to be able to take advantage of the large energy and luminosity reach [40]. To this end, an International Muon Collider Collaboration (IMCC) was formed based on a recommendation in the update of the European Strategy for Particle Physics [48]. The initial focus is on 10 TeV with an integrated luminosity of 10 ab^{-1}.

The main critical enabling technologies are 6D cooling of the muon beams, development of high field solenoids and accelerator magnets, very fast ramping magnets, high power targets, a proton driver, and potential strong beam instabilities. There has been recent progress in most of these areas demonstrating feasibility, but in the near term, a robust R&D program will be needed to bring the technology to the same level as linear or circular lepton colliders [40].

The scale of the R&D program can be expected to be a significant fraction of the final facility cost, much as for the linear collider program where a large fraction of a B$ has been invested in dedicated international test facilities beyond the Stanford Linear Collider. Some of the R&D could be done via an initial stage of 3 TeV at approximately half the cost of the 10 TeV version. Assuming sufficient funding to support a technically limited program and successful development of key technologies, it may be feasible to start colliding beams in the mid 2040's.

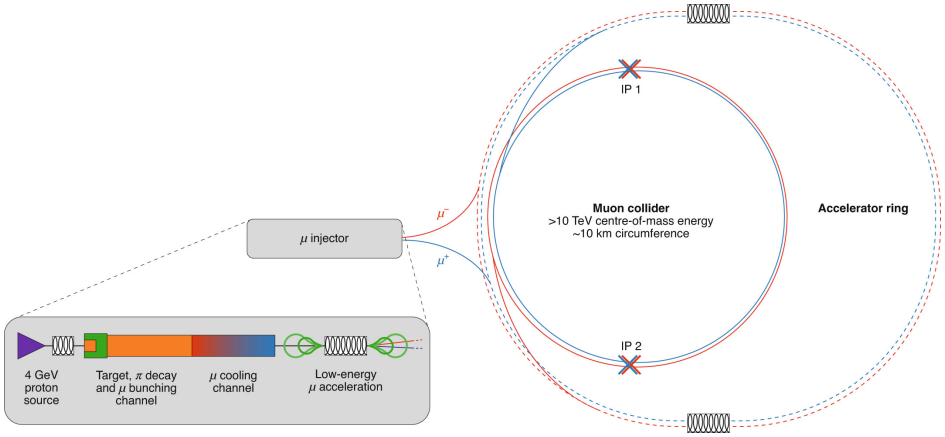

Figure 2-4. *A conceptual scheme for the muon collider (from Ref. [44])*

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Fermilab Site Fillers. Domestically, the US is fully engaged in the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE). However, given the long time-frame needed to plan and build large accelerator facilities, preparation for major new projects needs to start soon. Future energy frontier collider concepts that might feasibly be built on the Fermilab site include a 16 km circumference circular proton-proton collider with (24 – 27 TeV) c.m.e. and a staged muon collider from a Higgs factory at 125 GeV up to 8 – 10 TeV.

Each of the above options of hadron-hadron and muon colliders will require varying levels of R&D to produce a CDR by the time of the next Snowmass, ca. 2030. To accomplish this, it is proposed that the U.S. establish an integrated future colliders R&D program in the DOE Office of High Energy Physics (OHEP) to carry out feasibility studies and collaboratively engage in projects proposed abroad - see below Sec. 2.8.

Colliders based on wake-field acceleration concepts. These concepts are further discussed in Section 7.9.4 as an R&D topic because self-consistent parameter sets are not yet available – see Appendix 7.6 of Ref. [21] for the latest suggested parameters.

Electric fields due to charge separation in plasma can sustain >GV/m gradients and have enormous promise for accelerator technology - see, e.g., [49]. To date, several experiments demonstrated O(1-10 GeV) acceleration over 0.1-10 m long plasma channels. In principle, plasma wakefield (PWFA) linear accelerators can be employed in high energy e^+e^- and $\gamma\gamma$ colliders, but a significant long-term R&D effort is required to address many critical issues, such as acceleration of positrons, beamstrahlung, staging of multiple plasma acceleration cells, power efficiency, emittance control, jitter and scattering in plasma, etc [20], [40].

Structure wakefield acceleration (SWFA) has an advantage for application to linear colliders because the structures naturally accelerate electrons and positrons and are expected to be less challenging in preserving the beam emittance than plasma accelerators. Recent progress in development has increased the gradient to 300 MV/m and wakefield power generation to 500 MW [50].

2.5.2 Multi-TeV Colliders: main findings and recommendations

The ongoing Snowmass process has emphasized the emerging need to explore the Energy Frontier with particle collisions where the constituent center-of-mass energy is E_{cm} (c.m.e.) $\geq$ 10 TeV. Thus, the principal focus of the "Multi-TeV Colliders" group (AF4) has been a review of the machine options for hadron and lepton colliders that may provide a path to this threshold [51]. A consensus is emerging that the earliest timescale for making a construction decision for such a discovery machine will be sometime in the next decade. Thus, the evaluations were focused heavily on the maturity of the various concepts and the type of support that will be required to provide the HEP community with the design input required for a machine decision on that timescale or at the earliest date. Moreover there is the need to conduct the R&D and the integrated design work required for an equitable comparison of collider options during the course of the high luminosity LHC research program.

In addition to the frontier discovery machine concepts, various submissions were received describing lepton colliders that could operate in the 1-few TeV range, mostly as possible extended options of more mature Higgs factory designs. Furthermore, interest remains in the possibility of alternative paths exploring the TeV-scale including lepton-ion colliders and $\gamma\gamma$ colliders, with the latter perhaps driven by plasma or structure wakefields.

The AF4 evaluation of the various concepts - based on the current design maturity and R&D maturity - is as follows [51]:

- At present only a few design concepts have achieved a level of design maturity to have reliable performance evaluations based on prior R&D and design efforts. They are the linear e^+e^- collider ILC (1 TeV), CLIC (reaching 3 TeV c.m.e.), FCCeh, based on LHeC design and FCChh. Critical project risks have been identified and subsystem focus R&D is underway where necessary.

- Most of the emerging accelerator complexes still require significant basic R&D and design effort to reach a maturity level to be properly evaluated. Those could mainly profit from a directed R&D plan and a set of test facilities to demonstrate a broad range of technology concepts that are required. Dedicated demonstrators are generally necessary before a "reference" design can be completed. To this category it's easy to assign the SPPC hadron collider, muon colliders reaching c.m.e. 10 TeV and

the newly proposed $e^+e^-/\gamma\gamma$ colliders based on WFA. Moreover other lepton colliders with c.m.e. $\leq$5 TeV (multi-TeV ILC, ReLIC, CCC) still require further studies, as well as a Muon Ion Collider.

- It is clear that the concept of a Collider-in-Sea is not ready to be considered since a proof-of-principle R&D is required and the design is at a low level of maturity.

It should be noted that the concepts in the second (middle) category have the potential to achieve sufficient maturity within the next decade for evaluation by the HEP community. It is important to note that the necessary technical maturity for these concepts, and hence the ability to evaluate both the overall physics performance as well as cost scale, cannot be delivered without dedicated collider R&D research investment over the next several years, e.g., as in the proposed integrated collider R&D program, see Sec.2.8.

2.6 Snowmass'21 future colliders fora (AF-TF-EF)

2.6.1 e^+e^-Collider Forum: main findings and recommendations

The Snowmass'21 e^+e^- Collider Forum was organized by the Energy, Theory and Accelerator Frontiers and charged "...to promote dialogue and discuss differences and complementarities between the various e^+e^- collider concepts, either linear or circular, from the accelerator, detector and physics perspectives, in harmony with the rest of the wider international community". The Forum's activities - led by Maria Chamizo Llatas, Sridhara Dasu, Ulrich Heintz, Emilio Nanni, John Power, and Stephen Wagner - were carried out in close collaboration with the topical group conveners of the relevant frontiers. The Forum discussions covered a broad range of future electron-positron colliders from e^+e^- Higgs Factories - linear and circular - capable of providing a rich scientific program with sub-percent Higgs boson coupling measurements, to potential discovery machines for the next New Physics scales at O(10 TeV) c.m.e..

Key findings and recommendation of the e^+e^-Collider Forum report [52], related to accelerators, include:

- Higgs factories: primary consideration for the delivery of physics results is the start time of the physics program. Given the maturity of the technology, the ILC and the large storage rings hold the advantage of a possible early start of the program. The ILC and CEPC both discuss possible starts late in the 2030s. The FCC-ee would follow the HL-LHC program and start in the mid to late-2040s. C^3 discusses a start similar to that of ILC assuming the completion of a technology demonstrator. There is no published timeline for HELEN at this time.
- FCC-ee and CEPC have significant luminosity advantage and are able to complete the required runs at various luminosities faster but their larger civil engineering work requires significantly more time and cost. An early start of the civil engineering construction of a circular machine is therefore key to timely realization of physics.
- The ILC, HELEN and C^3 have cost, higher energy-reach, and polarization advantages but with lower luminosity, needing significantly longer running time to achieve the same level of precision for measurements compared to circular machines. From a potential siting point of view all but the C^3 and HELEN machines require greenfield sites.
- Given the strong motivation and existence of proven technology to build an e^+e^- Higgs Factory in the next decade, the US should participate in the construction of any facility that has firm commitment to go forward.

- Development of a $O(10)$-TeV scale e^+e^- machine based on wakefield acceleration with sufficient luminosity capability for $O(10)$ ab$^-$1 and energy-recovery technologies for improved power-to-luminosity costs, requires continued R&D investment. Corresponding accelerator R&D should focus on development of self-consistent machine design parameters and feasibility of attainment of collider specifications for the energy frontier.

2.6.2 Muon Collider Forum: main findings and recommendations

There has been a recent explosion of interest in muon colliders, as evident from a ten-fold increase in the number of related publications submitted to arXiv in the last couple of years. The topic generated a lot of excitement in Snowmass meetings and continues to attract a large number of supporters, including many from the early career community. In light of this very strong interest within the US particle physics community, Snowmass Energy, Theory and Accelerator Frontiers created a cross-frontier Muon Collider Forum in November of 2020. The Forum conveners - Kevin Black, Sergo Jindariani, Derun Li, Fabio Maltoni, Patrick Meade, and Diktys Stratakis (two from each of AF, TF, and EF) - invited many experts to give their perspective and to educate the broader community about physics potential and technical feasibility of muon colliders. It facilitated a strong bond and exchange of new ideas between the particle physics community and accelerator experts. Synergies with the neutrino and intensity frontiers, as well as overlaps with nuclear science and industry applications were also extensively discussed. Finally, the Forum served as an interface between the US community and the International Muon Collider Collaboration (IMCC) hosted by CERN.

Key findings and recommendation of the Muon Collider Forum report [53], related to accelerators, include:

- A multi-TeV muon collider offers a spectacular opportunity in the direct exploration of the energy frontier. Offering a combination of unprecedented energy collisions in a comparatively clean leptonic environment, a high energy muon collider has the unique potential to provide both precision measurements and the highest energy reach in one machine that cannot be paralleled by any currently available technology.
- Given the LHC results, a 10+ TeV lepton collider going beyond the classic precision versus energy dichotomy is an ideal machine.
- The accelerator challenges of a multi-TeV Muon Collider are now considered to be overcome based on the technological advances achieved over the past decade. Significant progress has been made in the development of high power targets and of high-field HTS solenoids, in the demonstration of operation of normal conducting RF cavities in magnetic fields, and in the self-consistent lattice designs of the various subsystems. No fundamental show-stoppers have been identified. Nevertheless, engineering challenges exist in many aspects of the design and targeted R&D is necessary in order to make further engineering and design progress.
- There is an established plan and funding for muon collider related R&D activities in Europe and it is imperative for Snowmass/P5 to reestablish R&D efforts in the US and to enable participation of US physicists in the International Muon Collider Collaboration (IMCC).
- The most fruitful path forward towards the development of a conceptual design of a Muon Collider would be the engagement of the U.S. community in the IMCC. The U.S. Muon Collider community is well positioned to provide crucial contributions to physics studies, further advance the accelerator technology and detector instrumentation, and explore options for domestic siting of a muon collider. An Integrated National Collider R&D Initiative discussed in Snowmass [54] can provide a much needed platform for R&D funding for such accelerator and detector development.

- Fermilab could be considered a candidate site for a Muon Collider with a center-of-mass energy reach at the desirable 10-TeV scale. The synergy with the existing/planned accelerator complex and neutrino physics program at FNAL is an additional stimulus for such investment of effort. A set of Muon Collider design options, with potential siting at FNAL, could be a goal contribution for discussions at the IMCC and the international committees to eventually form a global consensus decision on siting and selection of the Muon Collider. Having a pre-CDR document summarizing design for the FNAL-sited Muon Collider in time for the next Snowmass is a good goal. The preparation of such a document will require substantial, yet affordable, investment. Such an investment will reinvigorate the US high-energy collider community and enable much needed global progress towards the next energy frontier.

2.7 Implementation Task Force (ITF) analysis

The AF Implementation Task Force (ITF) was organized and charged with developing metrics and processes to facilitate a comparison between projects. The ITF is chaired by Thomas Roser (BNL) and comprises 11 additional world-renowned accelerator experts from Asia, Europe and the US, including two members of the Snowmass Young(the Snowmass'21 organization of early career researchers), and three EF and TF liaisons. Corresponding metrics have been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and *ep* collider facilities, based on traditional and advanced acceleration technologies. An additional group consisted of versions of the proposals that could be located at FNAL. More than 30 collider concepts have been comparatively evaluated by the ITF in terms of physics reach (impact), beam parameters, size, complexity, power, environment concerns, technical risk, technical readiness, validation and R&D required, cost and schedule. The ITF report documents the metrics and processes, and presents comparative evaluations of future colliders [21].

Summary Table 2-1 is a compressed version of the ITF report Tables 1-5 (see [21]) and lists the main parameters along with four columns with a summary value for technical risk (years of pre-project R&D needed), technically limited schedule (years until first physics), project costs (2021 B$ without contingency and escalation), and environmental impact (the most important impact is the estimated operating electric power consumption). The significant uncertainty in these values was addressed by giving a range where appropriate.

The years of required pre-project R&D is just one aspect of the technical risk, but it provides a relevant and comparable measure of the maturity of a proposal and an estimate of how much R&D time is required before a proposal could be considered for a project start (CD0 in the US system). Pre-project R&D includes both feasibility R&D, R&D to bring critical technologies to a technical readiness level (TRL) of 4-5, as well as necessary R&D to reduce cost and electric power consumption. The extent of the cost and power consumption reduction R&D is not well defined and it was assumed that it can be accomplished in parallel with the other pre-project R&D. Nevertheless this R&D is likely most important for the realization of any of these proposals. (Note that by using the proponent-provided luminosity values, ITF chose not to evaluate the risk of not achieving this aspect of performance. However, performance risk was included in the evaluation of technical readiness in the ITF report.) The time to first physics in a technically limited schedule is most useful to compare the scientific relevance of the proposals. It includes the pre-project R&D, design, construction and commissioning of the facility.

The total project cost follows the US project accounting system *but without escalation and contingency.* Various parametric models were used by ITF to estimate this cost, including the cost estimated by the proponents. The cost estimate uses known costs of existing installations and reasonably expected costs

for novel equipment. For future technologies, pre-project cost reduction R&D may further reduce the cost estimates used by the ITF.

Finally the electric power consumption is for a fully operational facility including power consumption of all necessary utilities. The ITF used the information from the proponents if they provided it, otherwise it made rough estimates based on expert judgement. Pre-project R&D to improve energy efficiency and to develop more energy efficient accelerator concepts, such as energy recovery technologies, have the potential to reduce the electric power consumption significantly from the values listed in the tables.

Any of the future collider projects will constitute one of the largest - if not the largest - science facilities in particle physics. The cost, the required resources and, maybe most importantly, the environmental impact in the form of large energy consumption will approach or exceed the limit of affordability. The ITF suggests that the Snowmass'21 final report recommends that R&D to reduce the cost and the energy consumption of future collider projects is given high priority.

2.8 Integrated Future Collider R&D Program proposal

It is widely recognized that future colliders are an essential component of a strategic vision for particle physics. Conceptual studies and technical developments for several exciting future collider options are underway internationally. The prevailing view of the global HEP community is that the next large collider facility should be an e^+e^- collider as a Higgs/EW factory. The physics case for such a collider is compelling, because it would enable the use of "the Higgs boson as a new tool for discovery," as envisioned in the 2014 P5 report. The community also recognizes that a collider beyond the capabilities of the HL-LHC, with energy reach to explore the ~ 10 TeV scale, such as a ~ 100 TeV hadron collider or a ≥ 10 TeV muon collider, will be necessary.

In order to realize a future collider, a concerted accelerator R&D program is required [54]. The U.S. HEP accelerator R&D program currently **has no direct effort in a collider-specific R&D area.** This gap – see Fig.2-5 – compromises worldwide progress on promising concepts, compromises the position of the U.S. as a leader in collider design and development, and limits national aspirations for a U.S. leadership role in particle physics.

In the course of the Snowmass'21 discussions, a new national integrated future colliders R&D program (IFC) in the DOE Office of High Energy Physics (OHEP) was proposed [54]. The overarching objective of the proposed program is to address in an integrated fashion the technical challenges of promising future collider concepts, particularly those aspects of accelerator design, technology, and beam physics that are not covered by the existing General Accelerator R&D (GARD) program. **The program will enable; (a) synergistic U.S. engagement in ongoing global efforts (e.g., FCC, ILC, IMCC) and (b) developing collider concepts and proposals for options feasible to be hosted in the U.S.**

The goal of the program is to inform decisions in down-selecting among (now numerous) collider concepts by the next European strategy update in 2025 - 2026, and the next Snowmass and P5 ca. 2030, to help move towards realization of the next collider as soon as possible and subsequently to advance towards a collider at a higher energy scale.

The characteristics of the proposed IFC program can be summarized as follows:

- Scope: sharply focused on future colliders; spans accelerator design, technology and full concept development; complements the existing HEP GARD program; multifaceted but selective and synergistic; integrates all critical R&D for a concept; priorities guided by P5;

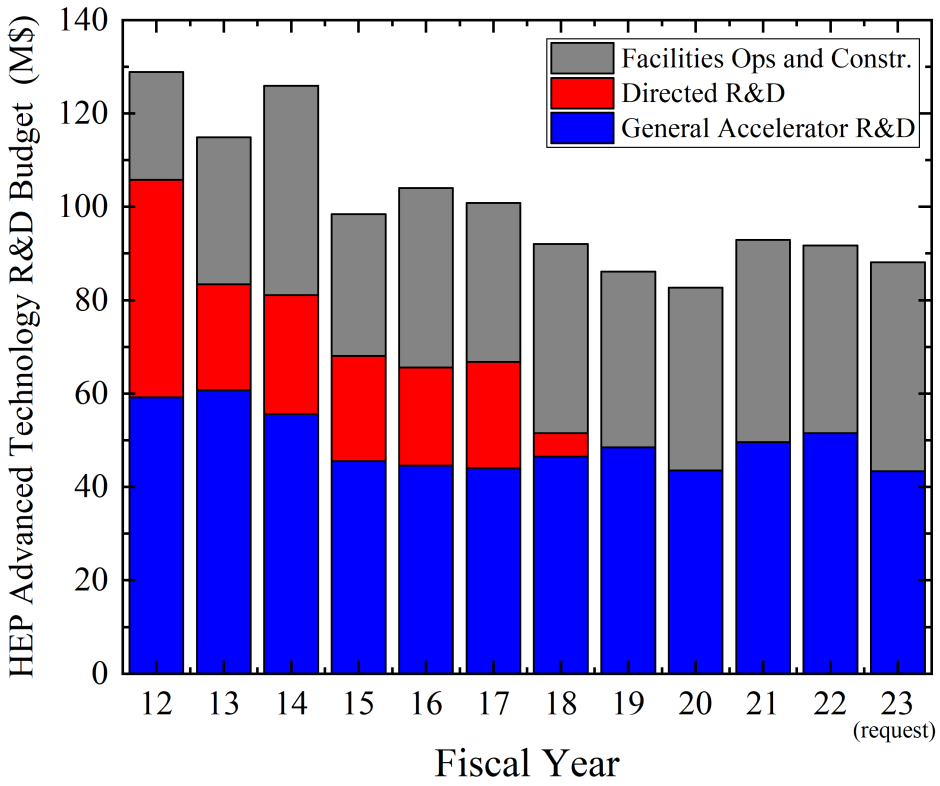

Figure 2-5. *Enacted US DOE OHEP budgets for general and directed accelerator R&D and corresponding test facilities operation and construction (FY12-FY22, in then USD, and FY23 budget request).*

- Organization: coherent national program; collaborative effort of U.S. national labs and universities;

- Coordination: centrally coordinated and funded; coordinated with global design studies and R&D; periodic assessment.

Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} cm^{-2}s^{-1}]	Yrs. pre-project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3]-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC[3]-0.38	0.38	2.3	0-2	13-18	7-12	110
CCC[3]	0.25	1.3	3-5	13-18	7-12	150
HELEN[3]	0.25	1.4	5-10	13-18	7-12	110
FNAL e^+e^- circ.	0.24	1.2	3-5	13-18	7-12	200
CERC[3]	0.24	78	5-10	19-24	12-30	90
ReLiC[1,3]	0.24	165 (330)	5-10	>25	7-18	315
ERLC[3]	0.24	90	5-10	>25	12-18	250
XCC $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
$\mu\mu$-Higgs	0.13	0.01	>10	19-24	4-7	200
ILC-3	3	6.1	5-10	19-24	18-30	∼400
CLIC-3	3	5.9	3-5	19-24	18-30	∼550
CCC-3	3	6.0	3-5	19-24	12-18	∼700
ReLiC-3	3	47(94)	5-10	>25	30-50	∼780
$\mu\mu$Collider[1]-3	3	2.3(4.6)	>10	19-24	7-12	∼230
LWFA-LC-3	3	10	>10	>25	12-80	∼340
PWFA-LC-3	3	10	>10	19-24	12-30	∼230
SWFA-LC-3	3	10	5-10	>25	12-30	∼170
FNAL$\mu\mu$[1]	6-10	20(40)	>10	19-24	12-18	∼300
LWFA-LC-15	15	50	>10	>25	18-80	∼1030
PWFA-LC-15	15	50	>10	>25	18-50	∼620
SWFA-LC-15	15	50	>10	>25	18-50	∼450
FNAL *pp* circ.	24	3.5(7)	>10	>25	18-30	∼400
FCC-hh[1]	100	30(60)	>10	>25	30-50	∼560
SPPS[1]	125	13(26)	>10	>25	30-50	∼400
LHeC	1.2	1	0-2 ?	13-18	<4	∼140
FCC-eh	3.5	1	0-2 ?	>25	<4	∼140
CEPC-SPPC-ep	5.5	0.37	3-5	>25	<4	∼300

Table 2-1. *Main parameters of the collider proposals evaluated by the ITF: Higgs/EW factories, multi-TeV lepton collider proposals (3 TeV c.m.e. options), colliders with 10 TeV or higher parton c.m.e., and the lepton-hadron collider proposals. The superscripts next to the name of the proposal in the first column indicate (1) total peak luminosity for multiple IPs is given in parenthesis; (2) energy calibration possible to 100 keV accuracy for M_Z and 300 keV for M_W; (3) collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes. The relevant energies for the hadron colliders are the parton c.m. energy, which can be substantially less than hadron c.m. energy quoted in the table. For each proposal, the ITF estimates are given on the years of pre-project R&D, years to first physics after decision to proceed, construction cost (including explicit labor, no escalation and no contingency), and facility electric power consumption (adapted from [21]).*

The proposed R&D program would facilitate the realization of future collider facilities, thereby ensuring the continuation of the fruitful endeavors of HEP in advancing the frontiers of our knowledge of the universe. It will also ensure the critical recruitment, development, and retention of a skilled workforce in accelerator science and technology.

2.9 Accelerator technologies and R&D

The cost of large accelerators is set by the scale (energy, length, power) and technology. Typically, accelerator components (Normal Conducting (NC) or/and Superconducting (SC) magnets and RF systems) account for $50 \pm 10\%$ of the total cost, while the civil construction takes $35 \pm 15\%$, and power production, delivery and distribution technology adds the remaining $15 \pm 10\%$ [55]. While the last two parts are mostly determined by industry, the magnet and RF technologies are linchpins in the progress of accelerators and without R&D the fraction of technological costs would be much higher.

To develop the necessary technology, as noted in Section 7.1.3, the US DOE OHEP General Accelerator R&D program supports R&D in five main thrusts: accelerator and beam physics (ABP), RF acceleration technology (NC and SC RF), magnets and materials, advanced acceleration concepts (AAC), and particle sources and targets. These programs and corresponding facilities operations were supported with a total of roughly 90M$ a year (see Fig. 2-5), distributed as estimated from FY19 as 36% for AAC, 22% for RF, 19% for materials and magnets, 15% for ABP, and 2% for targets and sources.

2.9.1 Superconducting magnet R&D

Superconducting magnets are required for many of the proposed facilities, in some cases with operational parameters well beyond current state-of-the-art, such as muon colliders or next generation high energy hadron colliders. This need was recognized by the last P5 process and the US Department of Energy-Office of High Energy Physics initiated the US Magnet Development Program (MDP) [56]; [57]. It is a general R&D program that pulls together US HEP magnet research groups at DOE laboratories and Universities under a common collaboration, with a focused mission and goals. MDP is closely collaborating with advanced magnet programs worldwide and has developed growing synergies with the NSF-funded National High Magnetic Field Laboratory; with other DOE offices, in particular, DOE-OFES; and with industry, both for conductor development and through the SBIR program. In the EU, the Particle Physics Strategy update process resulted in several recommendations for investments in critical technologies for future colliders and has resulted in the launching of the European High Field Magnet program (HFM) [58]. In Japan, superconducting accelerator magnet programs have been conducted at KEK for more than 40 years and have contributed to several international projects. In China, the primary focus is on Fe-based 12T magnets and high field hybrids utilizing Nb_3Sn and HTS. Superconducting Nb-Ti magnets used in the LHC operate close to the conductor limit at 8.3T. Dipole fields more than 16 T (up to 24 T) are needed, and solenoids, primarily for the muon collider, up to 50 T [59]. A recently tested US MDP prototype Nb_3Sn magnet has reached 14.5 T [6] - see Fig.7-6. The fastest rapid cycling magnets (required for a muon collider) have demonstrated up to 300 T/s ramp rates in an HTS-based superconducting magnet test at Fermilab [60]. Fields above 16 T require the use of high temperature superconductors (HTS); Bi-2212, REBCO and Fe-based, either in lieu of or combined in a hybrid scheme with Nb_3Sn.

Cost is a particular issue with all viable conductors beyond Nb-Ti. High cost slows R&D progress and would have a large impact on the cost of a future collider. Conductor cost reduction might be achieved through

a combination of continued R&D specific to cost reduction and development of industrial infrastructure through the recently launched Accelerator R&D and Production (ARDAP) Program. Also, there are already co-funded projects with Fusion Energy Sciences (FES, e.g. the Test Facility Dipole) and FES and fusion companies may be significant future magnet drivers. Superconducting detector magnets are a key component of particle physics experiments and have made significant progress over the past few decades. Further improvements will be required to cope with larger size, radiation loads and physics performance requirements.

A sizeable international magnet R&D effort over many years will be necessary to achieve the performance levels desired for many of the collider proposals now on the table. Historically, an international collaborative framework has proven to be critical in this area of technology.

As the HEP community explores its best options to enable future discoveries, magnet technology considerations are essential for informed decisions on the feasibility and cost of achieving the physics goals.

Successful projects have benefited from a combination of fundamental R&D by GARD and directed R&D. One example is the LHC Accelerator Research Program (LARP) that was started in 2004 as a directed R&D effort to develop Nb_3Sn IR Quadrupoles for the High Luminosity LHC. By 2013, it had achieved its main goals leading to the US LHC Accelerator Upgrade Project.

To maintain this highly successful approach and meet future challenges a new program has been proposed. The Leading-Edge technology And Feasibility-directed (LEAF) Program [61] would have a goal to achieve readiness for a future collider decision in the next decade.

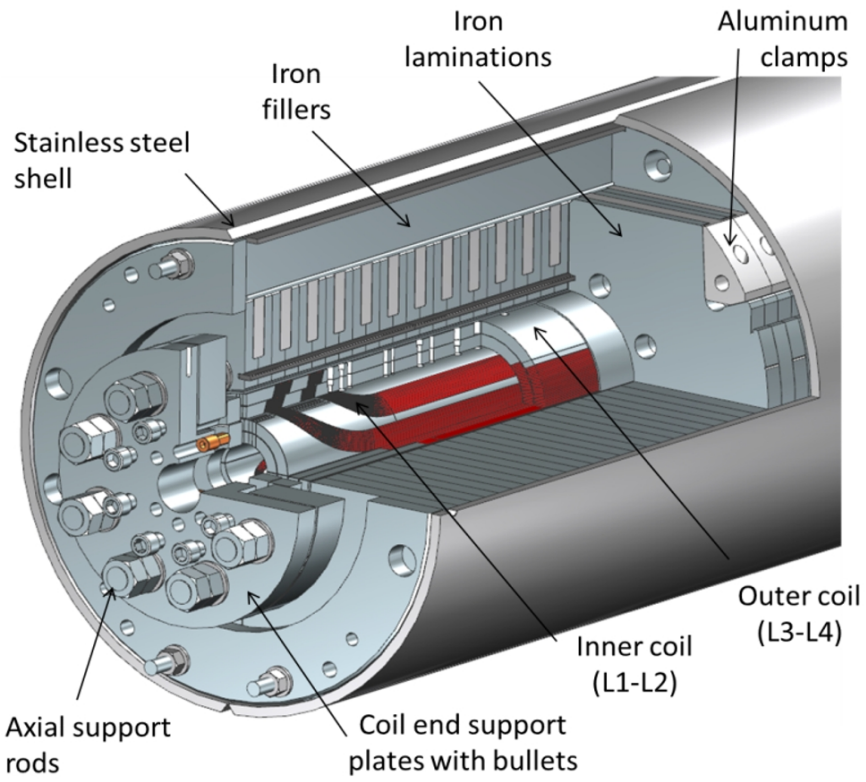

Figure 2-6. *15 T Nb_3Sn Magnet.*

2.9.1.1 Accelerator Technology - Magnets: main findings and recommendations

The U.S. Magnet Development Program (US-MDP) focuses on fundamental accelerator magnet R&D providing key magnet technologies which benefit all future accelerators.

- A successful ongoing national program with short- and long-term goals and plans, efficient management structure, established staff, and facilities.
- Well-recognized internationally, actively participate in international magnet R&D activities.
- Superconducting magnet technology is critical to most of the proposed colliders and new experiments and strong engagement from the magnet community on future collider roadmaps is critical to ensure success.

Discussions and initiatives emerging from the Snowmass'21 process motivate enhanced scope and significant increase in resources to prepare accelerator magnet technology, e.g. [62]:

- Enhance MDP scope and resources to address general magnet R&D needs for HEP, including magnet design and short model development for specific accelerator applications, e.g. muon collider
- In addition, invest in critical technology scale up and cost reduction efforts, and preparation for industrialization, with the goal of providing magnet technology readiness for future projects and a sound basis for future facility specifications and costing.
- Explore opportunities to reduce power requirements for facility operation
- Provide support for test facility upgrades and operation

2.9.2 RF technology R&D

Accelerator radio frequency (RF) technology has been and remains critical for modern high energy physics (HEP) experiments based on particle accelerators. Tremendous progress in advancing this technology has been achieved over the past decade in several areas. These achievements and new results expected from continued R&D efforts could pave the way for upgrades of existing facilities, improvements to accelerators already under construction, well-developed proposals and/or enable concepts under development.

The ongoing RF technology R&D efforts closely follow the decadal roadmap that was developed in the framework of the DOE General Accelerator R&D (GARD) program in 2017. The roadmap reflects the most promising research directions that can potentially enable future experimental HEP programs. Similar to the DOE GARD roadmap, the European particle physics community developed a roadmap for European accelerator R&D presented in a report that includes a roadmap for high-gradient RF structures and systems. The two roadmaps cover similar RF technology topics thus presenting opportunities for collaboration between the U.S. and European institutions.

The highest gradient large-scale NC RF system is the 28 MeV/m linac of the SwissFEL at the PSI (Switzerland). Up to 100 MV/m accelerating beam gradients were achieved in the CLIC 12 GHz structures at the CERN test facility, while up to 150 MV/m gradients were reported in the first test of short 11.4 GHz NC structures cooled to 77 K at SLAC [25] - Fig.2-7. As for SRF, the largest scale accelerator to date is the 17.5

GeV 1.3 GHz pulsed linac of the European XFEL at DESY that has achieved an average beam gradient of roughly 23 MV/m with a nominal Superconducting RF (SRF) cavity quality factor of $Q_0 \simeq 1.4 \cdot 10^{10}$ at 2 K. The full ILC specification on the beam acceleration gradient of 31.5 MV/m has been demonstrated at the FNAL FAST facility [3]. Recent advances in SRF cavity processing such as *nitrogen doping* allow further improvement of the quality factor to $(3-6) \cdot 10^{10}$ (hence, reducing the required cryogenic cooling power) and an initial cryomodule for the LCLS-II-HE, operated at 25 MV/m with a $Q_0 = 3 \cdot 10^{10}$. Further R&D aims for 50 MV/m gradients in 1.3 GHz structures [63]. An active ongoing accelerator R&D program for future multi-MW proton beams includes development of more efficient power supplies with capacitive energy storage and recovery, more economical RF power sources such as 80% efficient klystrons, magnetrons, and solid-state RF sources (compared to current $\sim$ 55%) see for example [64]; [65].

2.9.2.1 Accelerator Technology - RF: main findings and recommendations

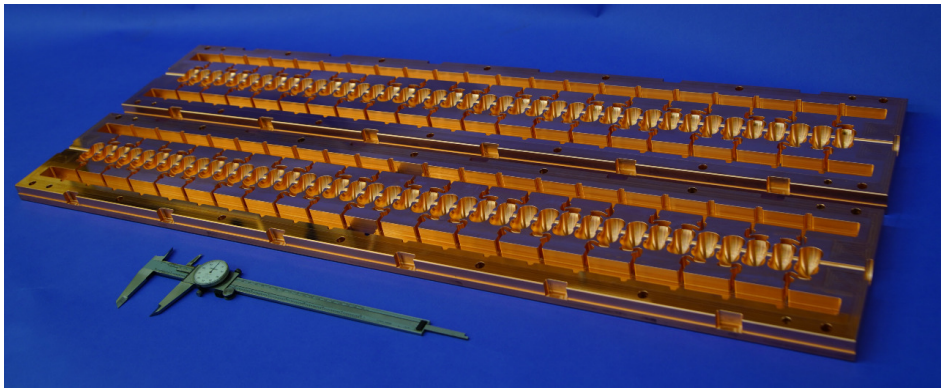

Figure 2-7. *Both halves of the C^3 prototype structure prior to braze. The one meter structure consists of 40 cavities. A RF manifold that runs parallel to the structure feeds 20 cavities on each side. The structure operates at 5.712 GHz - from [64]*

The GARD roadmap continues to serve as community-developed guidance for RF technology R&D, but based on recent progress it would benefit from some mid-course corrections. Based on the discussions and submitted White Papers, the following are key directions that should be pursued during the next decade [66]:

- Studies to push performance of niobium and improve our understanding of SRF losses and ultimate quench fields via experimental and theoretical investigations.
- Developing methods for nano-engineering the niobium surface layer and tailoring SRF cavity performance (shunt impedance, Q-factor and gradient) to a specific application, e.g., a linear collider, a circular collider, or a high intensity proton linac.
- Investigations of new SRF materials beyond niobium via advanced deposition techniques and bringing these materials to the point where they can be used in accelerators.
- Developing advanced SRF cavity geometries to push accelerating gradients of bulk niobium cavities to approximately 70 MV/m for either an upgrade of the ILC or compact SRF linear collider.
- Pursuing R&D on companion RF technologies to mitigate field emission, provide precise resonance control, etc.
- Research on application of SRF technology to dark sector searches, such as axions.

- R&D on high-gradient normal conducting RF structures operating at cryogenic temperatures with a gradient of greater than 150 MV/m as a promising way toward a compact linear collider.
- R&D on high frequency and multi-frequency structures to transcend limits on shunt impedance and accelerating gradients.
- Investigation of novel materials and manufacturing techniques to improve high gradient performance and remove design constraints.
- Developing high efficiency, low-cost RF sources that would benefit many operating and practically every future intensity or energy frontier machine.
- Studies dedicated to industrialization and cost reduction of fabricating RF components and systems.
- Continue research on advanced SWFA structures to bring them closer to practical applications.
- Experimental and theoretical research to further our understanding of the RF breakdown physics.
- Continued development of computational tools for multi-physics and virtual prototyping.
- Developing a community ecosystem for accelerator and beam physics modeling that would incorporate a comprehensive set of high-performance simulation tools for RF-based accelerators.

To support these key research directions, there is a need to upgrade the existing or build new R&D and test facilities that have the capabilities to investigate the new concepts and help integrate them into systems with ready access to researchers.

2.9.3 Targets and sources R&D

The next generation of high power targets for future accelerators will use more complex geometries, novel materials, and new concepts (like flowing granular materials [67]). Under active development are advanced numerical approaches that satisfy the physical design requirements of reliable beam targets [68]. In parallel, there is work to be done on radiation hardened beam instrumentation [69], development of irradiation methods for high power targets and irradiation facilities [70].

There are challenges in high-intensity high-brightness beam sources for future accelerators. They are particularly formidable for sources of beams with special characteristics, such as polarized electrons and ions or ultra-small emittances, and for tertiary and secondary particles, such as muons and positrons. In the longer run, high intensity positron sources, that are critical for future e^+e^- linear colliders, may be simplified using advanced accelerator concepts and photon-driven schemes that can potentially outperform conventional e^+ production techniques [71].

2.9.3.1 Accelerator Technology - Targets and Sources: main findings and recommendations

Key recommendations of the Snowmass'21 AF7 topical group ("Accelerator Technology - Targets and Sources") include [72]:

- Develop or upgrade Post-Irradiation Examination (PIE) facilities that will allow testing activated novel materials.

- Develop and validate alternative beams that mimic the effects of high-energy proton irradiation.
- Develop irradiation stations relevant to assess radiation damage in various materials.
- Develop and validate numerical tools to predict radiation damage.
- Develop novel concepts and novel target materials.
- Develop radiation-resistant sensors for better numerical validation of the structural and thermal simulations.
- Strengthen the high-power target community through the RaDIATE collaboration and High-Power Targetry workshops.
- Leverage the synergy with other communities facing similar challenges (light source facilities, Accelerator Driven Systems and fusion).
- Advance the state of development of a 4th generation Electron Cyclotron Resonance Ion Source (ECRIS) that can be achieved using higher magnetic fields.
- Accelerate development of high intensity positron sources including the use of advanced accelerator concepts.
- Continue development of high brightness, high average current sources (DC, RF and SRF guns) and explore applying machine learning to advance source performance and stability.
- R&D in high current electron guns is needed for efficient charge breeding of high-intensity beams.
- Development of cathode testing facilities is critical.

2.9.4 Advanced acceleration concepts

Wakefields driven in plasmas or advanced structures offer high accelerating gradients, and R&D is in progress to develop future collider options. Plasma waves can be effectively excited by short and powerful external drivers. A benefit of plasma acceleration is that plasma is not limited by the conventional RF breakdown processes as, in some sense, it is already broken down and thus acceleration gradients of many GV/m are possible. Three effective ways to excite plasma have been demonstrated in the past two decades: i) by intense electron bunches – 9 GeV acceleration over 1.3m at 10^{17}cm^{-3} has been achieved at the SLAC FACET facility [73]; ii) by short laser pulses – an electron beam energy gain of up to 7.8 GeV over 20 cm in a few 10^{17}cm^{-3} plasma observed at the LBNL BELLA facility [74]; and iii) by self-modulated high energy proton bunches – 2 GeV gain over 10m at 10^{15}cm^{-3} reported by the CERN AWAKE experiment [75].

There are three remarkable recent developments on the way to practical plasma-based beam accelerators: i) EuPRAXIA has been included in the ESRFI 10-20 yrs roadmap [76] (EuPRAXIA is a 569 MEuro European plasma accelerator project *proposal*, supported by 50 institutions from 15 countries, and aiming for 5 GeV electron beam acceleration and development of plasma-based FELs); ii) the laser wakefield accelerator at SIOM/CAS in Shanghai (China) has achieved an accelerated 0.5 GeV electron beam (produced by a 200 TW laser exciting plasma in a 6 mm He gas jet) sufficient for initiation of the FEL generation of 27 nm light in the downstream undulators – making it the first demonstration of a plasma-based FEL [77]; and iii) a similar free electron lasing demonstration at the LNF-INFN with a beam-driven plasma accelerator [78].

In addition to plasma acceleration, relativistic electrons or positrons passing near a material boundary will produce wakefields when the particle velocity exceeds the Cherenkov radiation condition. The longitudinal wakes can be used to accelerate an appropriately phased trailing beam [79] or can be extracted by a high efficiency RF coupler as a high power RF source [80]. The CLIC linear collider design is an example of using 'structure wakes' to power a linac. There has also been significant progress on another approach that utilizes laser-driven microstructure accelerators [81].

Structure wakefield acceleration (SWFA) has an advantage for application to linear colliders because the structures naturally accelerate electrons and positrons and are expected to have smaller challenges preserving the beam emittance than plasma accelerators. Recent progress in development has increased the gradient to 300 MV/m and wakefield power generation to 500 MW [50]. The next proposed steps are to design, construct and test a laboratory-scale SWFA module and incorporate it into a SWFA-based facility design with the intent of implementing a dedicated test facility as a scalable demonstration of the technology aimed at an energy frontier machine.

In principle, wakefield-based linear accelerators can be employed in high energy $e^+e^-/\gamma\gamma$ colliders, but a significant R&D effort is required to address many critical issues, such as acceleration of positrons, staging of multiple plasma acceleration cells, power efficiency, emittance control, jitter and scattering in plasma, beamstrahlung, etc [20], [40]. New concepts continue to emerge that may address known challenges or further expand capabilities.

2.9.4.1 Advanced Acceleration Concepts: main findings and recommendations

The AF6 Topical Group focused on understanding the limits, the state of the design concepts, and the status of the R&D for plasma and structure wakefield acceleration. At this time, there are no parameter sets for a plasma or structure based linear collider that self-consistently address the known accelerator physics challenges – see Appendix 7.6 of Ref. [21] for the latest suggested parameters. However, acceleration of beams with ultra-high gradients (GV/m and beyond) will reduce the dimensions and thus potentially reduce the costs and power consumption of future high energy physics machines with the potential to offer e^+e^- and $\gamma\gamma$ colliders at and beyond 15 TeV. Recognizing this promise, the last Snowmass and P5/HEPAP recommended, and DOE developed with the community, an organized Advanced Accelerator Development Strategy, and work has been aligned to this strategy.

Over the last 15 years, three major facilities for advanced accelerator research have been constructed and operated in the US: FACET, BELLA, and AWA. A number of important milestones have been achieved including multi-GeV acceleration in a single stage, limited positron acceleration, efficient local loading of the structure, the first staging of plasma accelerators, and demonstration of beam shaping to improve efficiency in plasmas and structures. Details, including references, describing the status and needs of the field can be found in the AF6 Topical Group Summary [82].

In order to move forward, a vigorous R&D program will be required. The US is in a good position in this respect with several state-of-the-art of beam test facilities mainly dedicated to research in the advanced accelerator field, including FACET-II, BELLA, ATF, AWA and FAST-IOTA as well as numerous universities. As described, vigorous R&D using these facilities and programs is needed to push forward the key next steps in the Development Strategy including staging of multiple modules at multi-GeV, high efficiency stages, preservation of emittance for electrons and positrons and shaped beams, as well as the development of efficient, low-cost and high repetition rate drivers.

The development of self-consistent parameter sets for compact high-gradient colliders addressing the known physics challenges is critical to guide the efforts and provide a clear and actionable R&D path for an HEP

facility. Studies should provide detailed examples of how the main challenges can be addressed and clarify where experimental demonstrations, or detailed simulations of the relevant sub-systems, are needed. In addition, cost estimates, including the impact of some of the stringent component tolerances, should be made to understand if the potential cost benefit of the new technologies can be realized.

Developing the parameters and pursuing the R&D may require funding that has not been available to date. The European roadmap for accelerators [40] includes a full chapter on advanced accelerators and is well-aligned with our call for an organized integrated design study. Even though the advanced accelerator field was born and is still squarely centered in the US, it is telling that the most recent high profile plasma-based FEL demonstrations occurred in Europe and Asia. This kind of research in the US is unfortunately not seen as directly impacting HEP, putting in jeopardy the US leadership in the field.

The explicit suggestions from the AF6 working group [82] focus on priority research to continue to address and update the Advanced Accelerator Development Strategy:

- Vigorous research on advanced accelerators including experimental, theoretical, and computational components should be conducted as part of the General Accelerator R&D program. This will advance the advanced accelerator R&D roadmaps towards future high energy colliders, develop intermediate applications, and ensure international competitiveness. Priority directions include staging of multiple modules at multi-GeV, high efficiency stages, preservation of emittance for electrons and positrons, high fidelity phase space control, active feedback precision control, and shaped beams and deployment of advanced accelerator applications.

- A targeted R&D program addressing high energy advanced accelerator-based colliders (e.g. to 15 TeV, with intermediate options) should develop integrated parameter sets in coordination with international efforts. This should detail components of the system and their interactions, such as the injector, drivers, plasma source, beam cooling, and beam delivery system. This would set the stage for an integrated design study and a future conceptual design report, after the next Snowmass.

- Research in near-term applications should be recognized as essential to, and providing leverage for, progress towards HEP colliders. The interplay and mutual interests in this area between Offices in DOE-SC including HEP, BES, FES and ARDAP as well as with NSF, NNSA, defense and other agencies should be strengthened to advance and leverage research activities aimed at real-world deployment of advanced accelerators.

- Advanced accelerators should continue to play a key-role in workforce development and diversity in accelerator physics. University programs and graduate students greatly benefit from the scientific visibility of the advanced accelerator field. Access to user facilities for graduate students and early career researchers as well as formal and hands on training opportunities in advanced beam and accelerator physics should be continued and enhanced.

- Enhanced driver R&D is needed to develop the efficient, high repetition rate, high average power laser and charged particle beam technology that will power advanced accelerator colliders and societal applications.

- Support of upgrades for Beam Test Facilities are needed to maintain progress on advanced accelerator Roadmaps. These include development of a high repetition rate facility, proposed as kBELLA, to support precision active feedback and high rate; independently controllable positrons to explore high quality acceleration, proposed at FACET-II; and implementation of a integrated SWFA demonstrator, proposed at AWA.

- A study for a collider demonstration facility and physics experiments at an intermediate energy (c.a. 20–80 GeV) should establish a plan that would demonstrate essential technology and provide a facility for physics experiments at intermediate energy.
- A DOE-HEP sponsored workshop in the near term should update and formalize the U.S. advanced accelerator strategy and roadmaps including updates to the 2016 AARDS Roadmaps, and to coordinate efforts.

2.9.5 Accelerator and Beam Physics and Accelerator Education

Accelerator and beam physics (ABP), the science of charged particle beams, is an essential aspect of designing and building the next frontier accelerators. A robust and scientifically challenging program in accelerator and beam physics is critical for the field of particle physics to be productive and successful. Major ABP challenges aim at improving the reliability, performance, safety, and cost reduction of future accelerators and push the envelope of beam intensity, beam quality, beam measurement and control, and development of methods to model and predict beam behavior.

There are many notable recent developments in the physics of beams. For example, several novel cooling schemes were experimentally demonstrated at operational accelerators. A true breakthrough was the demonstration of the *ionization cooling* of 140 MeV/c muons at the MICE experiment at RAL (UK) – some 10% beam emittance reduction was observed in a single pass through the cooling section [4]. In 2020, *"bunched" electron beam cooling* of ions in RHIC ($\gamma \sim 5$) – remarkable by the pioneering use of high quality bunched electron beams from an electron beam RF photoinjector gun (before, only DC electron accelerators were used with limited capability to get to very high energies) – was demonstrated at BNL [83]. In 2021 the Fermilab team successfully carried out a proof-of-principle experiment on the *optical stochastic cooling* of 100 MeV electrons in the IOTA ring in which the use of undulator magnets - instead of electrostatic pickups in traditional stochastic cooling setups - expanded the feedback system bandwidth by several orders of magnitude to the THz range [84].

Efforts have been ramping-up in recent years to use Artificial Intelligence and Machine Learning (AI/ML) to enhance the performance of accelerators and beamlines [85,86]. There is significant promise of applications of AI/ML in beam diagnostics, controls, and modeling [87]. Opportunity exists in broadening AI/ML methods for early detection of a broad range of accelerator component or subsystem failures [88] and for optimization of advanced numerical simulations through identification of the most promising combinations of parameters thereby reducing the total number of required simulations [89].

Future circular and linear e^+e^- colliders require collision optimization studies including the 3D beam size flip-flop from the beam-beam effect, large dynamic aperture Interaction Region (IR) design; pico-meter vertical emittance preservation techniques in high-charge circular colliders with strong focusing IRs, effects of detector solenoids, and beam-beam effects; end-to-end emittance preservation simulations for linear colliders augmented with experimental tests of beam-based alignment techniques in the presence of realistic external noise sources; plasma-lens-based final focus and beam transport system designs [90, 91].

Required ABP explorations for future hadron colliders include efficient collimation techniques [92], electron lenses for Landau damping and collimation [93], dynamic aperture optimization methods to make possible new integrable optics solutions [94], and studies to obtain lower emittances from new particle sources for injecting beams in high-bunch-charge colliders.

A recent community exercise summed up the needs and directions of future developments in ABP [95]. Among many, those include issues related to beam loss control in high-intensity high-power accelerators (space-charge

effects, instabilities, collimation, electron lens compensation, integrable optics, etc) which require innovative approaches, theoretical and experimental studies (at, e.g., the IOTA ring [96], and operational accelerators in the US and abroad) and validated computer models/codes. A key challenge would be to reduce particle losses (dN/N) at a faster rate than increases in achieved beam intensity (power) (N) [8].

Traditionally, HEP has played a leading role in education and workforce training for particle accelerators. Currently, this task is surely shared by other SC offices, e.g., NP (that will need a significant workforce for the EIC) and BES (e.g. for operational and future X-ray sources and spallation neutron sources), that plan building new or upgrading existing facilities in the next decades - all of these need trained and talented accelerator personnel. Naturally, the EIC and other SC accelerator projects will also provide an excellent training ground for personnel that would, in the future, be needed for HEP machines, such as high intensity proton sources and high energy colliders. All that requires a shared vision on accelerator workforce development and R&D with NP and BES. The DOE OHEP should take a lead in organizing corresponding discussions within the accelerator community and formulation of an integrated vision across the Office of Science and NSF.

2.9.5.1 Accelerator and Beam Physics and Accelerator Education: main findings and recommendations

The physics limits of ultimate beams indicate that it will be very difficult to reach an order of magnitude higher energy beyond currently proposed future colliders such as ILC, FCC and CEPC with today's conventional accelerator technology. Hence, intensified R&D in advanced beam physics and accelerator technologies is needed to address known challenges and reach ultimate beams.

On the contrary, support for fundamental beam physics research has been declining. In the 2010's, the NSF reduced its support of Accelerator Science while funding by DOE through GARD and Accelerator Stewardship has been steady in then-year dollars, thereby declining with inflation - see Fig.2-5. With the energy frontier shifted from the US to Europe, collider expertise, particularly in e^+e^- and muon colliders, has not been able to maintain a healthy profile. In addition to slowing advancement, it makes it difficult to maintain a viable R&D portfolio and threatens student training and work-force development in US accelerator science. Integrated efforts are needed to mitigate this situation and maintain at adequate levels the Beam Physics and Accelerator Science & Engineering (AS&E) education and outreach programs in the US.

A robust and scientifically challenging R&D program in accelerator and beam physics is needed to position the field of US High Energy Physics to be productive and competitive for decades to come. Corresponding recommendations of the AF1 topical group include [97]:

- Continuous reduction of the inflation-adjusted budget of the OHEP GARD program in general and ABP program should be stopped, and the level of support adequate to the challenges ahead of the ABP thrust should be secured;
- Establishment of a decadal road map of accelerator and beam physics research in the DOE OHEP General Accelerator R&D (GARD) program to address the four ABP *Grand Challenges* in beam intensity, quality, control and prediction [98] ;
- Re-establish a program of beam physics research on general collider related topics towards future e^+e^- and muon colliders;
- Strengthen and expand capabilities of the US accelerator beam test facilities to maintain their competitiveness with respect to worldwide capabilities.

To build and maintain a strong diverse and inclusive workforce to support future HEP accelerator facilities, we also propose that the community pursue the following efforts to further strengthen Beam physics and Accelerator Science & Engineering (AS&E) education and outreach program:

- Gather integrated statistics on workforce composition and needs as well as gender, and ethnicity for AS&E students and workers in the labs, universities, and industry to monitor progress and better guide long-term efforts. This can be achieved by extending roles of the USPAS.
- The AS&E field should organize a yearly undergraduate level recruiting program structured to draw in talent broadly and also enhance recruiting of women and underrepresented minority (URM) students. This could be coordinated with the USPAS.
- Increase US Particle Accelerator School (USPAS) office effort by one FTE to extend roles listed above to benefit the community; improve technical IT support of classes; and for long-range planning and stability.
- Strengthen accelerator research at universities by funding professors and projects on campus and in collaborative lab efforts to increase visibility among undergraduates to recruit talent into the field.
- Lower the barriers to participation women and URM talent into the field and take concrete measures to improve discourse and support quality of life and family support issues at the labs to broadly retain talent. Recommended steps are detailed in the Education, Outreach, and Diversity section.

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3

Community Engagement Frontier

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3.1 Introduction

In Snowmass 2013, investigations into HEP community engagement addressed physics Communication, Education and Outreach (CE&O) [1], and this was the first time HEP incorporated such activities into the Snowmass process. The CE&O Frontier organized its Working Groups according to the target audiences of the General Public, Policy Makers, Science Community, and grade 5-12 Teachers and Students. The framework for all CE&O efforts consisted of three main outcome goals: ensuring the resources needed for the US to maintain a leadership role in HEP research, ensuring the public realizes how valuable and exciting particle physics is, and ensuring US HEP produces a talented and diverse pool of STEM professionals. Common themes of action to meet those goals emerged across the Working Groups: making a coherent and unified case for HEP, instituting real recognition for colleagues engaged in CE&O activities, providing more CE&O resources and training for our community, and creating a central team tasked with supporting HEP CE&O efforts.

Each Snowmass 2013 CE&O Working Group produced a number of specific recommendations for implementation to help achieve the CE&O goals. In the intervening years since the release of the CE&O Frontier Report, many individuals and institutions accomplished much in following several of those recommendations. Great examples can be found in the area of public policy. A small group of people developed sophisticated, powerful and efficient database and wiki tools that have transformed and multiplied our HEP Congressional advocacy efforts. Another major communications success for the HEP community during this last P5 era has been the development and consistent delivery of a coherent, unified message about the US HEP program to Congress and other audiences. On the other hand, our field essentially set aside many of those recommendations. The community did not create a central or national team to support CE&O work, nor did it put in place many institutional incentives to encourage that work among our colleagues. Although much good work was done by many, implementation of CE&O recommendations has been spotty and incoherent overall.

The Snowmass 2013 experience absolutely did make clear that it is crucial to address community engagement for the health of US HEP. In fact, leadership within the field realized from the very beginning of the Snowmass 2021 process that community engagement needed to be expanded into a Community Engagement Frontier

(CEF) with full scope over all areas of community engagement (i.e. a much broader scope than CE&O from 2013), and co-equal with the physics frontiers. The structure of this expanded Community Engagement Frontier includes seven Topical Groups defined primarily by general issues to be addressed: Applications and Industry; Career Pipeline and Development; Diversity, Equity and Inclusion; Physics Education; Public Education and Outreach; Public Policy and Government Engagement; and Environmental and Societal Impacts. The overall objective is to improve and sustain strategic engagements with our communities in order to draw support for and strengthen the field of particle physics (an inward-focused goal carried forward from Snowmass 2013), while playing key roles in serving those communities (an outward-focused goal added for Snowmass 2021). Arranging the Topical Groups by issue proved to be a very efficient structure that brought great focus to the efforts of the Groups which, succinctly, aim to support: practical applications of research in particle physics and technology transfers to industries; career development and job opportunities for young scientists; encouragement and inclusion of diverse physicists to reflect the diversity in our communities; advances in physics education to produce talented and qualified students; engagement with the public to share in the essence and importance of physics research; partnerships with governments and policymakers to grow the scientific enterprise; and improvements in the ways that our field affects the environment and society in which we live.

The issues addressed by the CEF Topical Groups are relevant to all the other frontiers of Snowmass 2021 — they are crosscutting topics or issues for all the physics frontiers. About one hundred letters of interest (LOI) were received on these topics. These LOIs were condensed into thirty-five contributed papers, the details of which are mentioned in the Topical Group Reports. In addition to the LOIs, inputs to contributed papers came from town hall discussions, group meetings, expert speaker invitations, workshops, and surveys. Sections 3.2–3.8 of this report summarize the work done by the Topical Groups, and the individual Topical Group Reports for CEF01 [2], CEF02 [3], CEF03 [4], CEF04 [5], CEF05 [6], CEF06 [7] and CEF07 [8] document the details and the specific recommendations for improving the ways our community engages in these areas.

3.1.1 Overall Community Engagement Frontier Goals

Structuring the CEF work into the seven issue-based Topical Groups defined above was a very effective strategy for organizing and maximizing the productivity of the people working in the Frontier. However, two categories of overlaps necessitate a different organizing principle for setting overall implementation goals for CEF. First, the shared experiences and overlapping interests among the various Topical Groups and other frontiers mean that different groups are often addressing the same issue from different directions or perspectives, and we need to continue following the guiding principle of coherence to our efforts. Second, there are often two or more very different recommendations related by a common target audience. Bringing those recommendations together could very well result in more efficient and effective engagement. These considerations informed the development and incorporation of strategies and recommendations articulated in a set of overarching goals for HEP engagement with five interrelated communities: HEP itself, K-postdoc education, private industry, government policy, and the broader society (Figure 3-1). These overall CEF goals organized by target community for engagement actually echo the Snowmass 2013 working group structure. The goals along with references to the specific Topical Group sections informing each goal are listed below.

HEP Internal Engagement

It is often said that you can tell much about a group of people by considering how they interact with each other and conduct their own affairs. Therefore, a reasonable place to begin a study of HEP Community

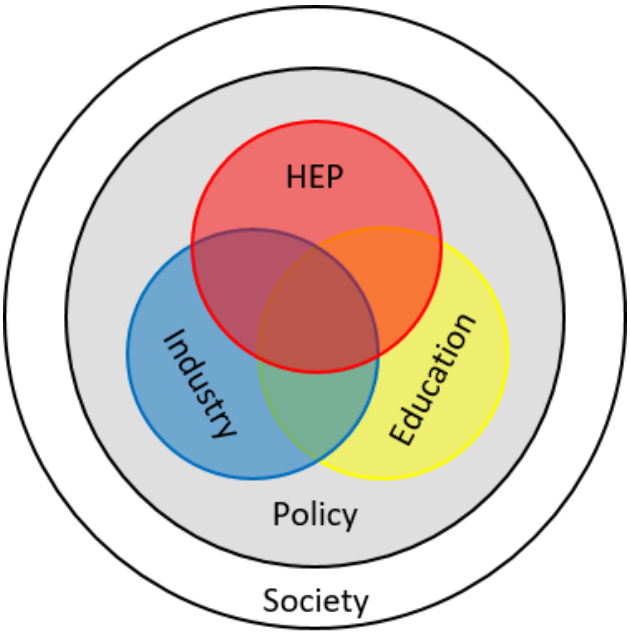

Figure 3-1. *Five interrelated communities targeted for HEP engagement.*

Engagement is to analyze how the HEP community engages with itself. What are the characteristics of the ways that we build and organize our own community of colleagues? What values do we embody by our choices of which activities are incentivized (or not) in our work? Every single CEF Topical Group confronted these questions at varying levels. In fact, a plurality of recommendations put forward by the seven Groups were directed inward, suggesting improvements to the standard operating procedures of the US particle physics community.

It is widely known that science broadly is a discipline which lags behind most others in its membership diversity along multiple axes. Physics, and HEP in particular, have been less successful than most other science fields in realizing much improvement in this area over the years. It has become clear that a factor contributing to this limited success is the fact that the pool from which we draw professional talent is a small one dominated by traditional physics programs at a select group of R1 academic institutions. This must change for HEP to access the depth of talent from the broader society. At the same time, individuals who do bring greater diversity to our field often encounter barriers to full participation and advancement in their careers. The norms of interaction developed over decades by a fairly homogeneous community can serve to alienate those possessing a potential to enrich our field with different backgrounds and perspectives. It is not only beneficial, but also simply good manners to present a welcoming environment to new colleagues and neighbors.

Most particle physicists are receptive to participation in Community Engagement activity, and many are quite active in this work. However, there are strong pressures within HEP that serve to prevent many members, especially early career members, from significant participation. The first of these is time. HEP research is a demanding task requiring great resources, not the least of which is time. There are always schedules to follow, deadlines to meet, tasks to complete. Particularly for postdocs and junior faculty working to establish themselves in the field, it is a tall order to expect them to sacrifice research time for community engagement efforts. The competition for the next job or promotion is fierce, and time "lost"

equates to falling behind one's peers in career achievement. This leads to the second pressure, which is the fact that records of successful participation in community engagement tasks have rarely been given strong consideration by hiring or promotion evaluation committees at our labs and universities. There are signs that this may be changing, as cases of work such as "outreach" being included in the "service" portion of committee evaluations is more common than it once was, and NSF has long encouraged attention to similar efforts through its grant requirement to address broader impacts.

In the P5 era since Snowmass 2013, US HEP has become renowned for its record of project management. Until now, that success has primarily relied on maintaining a proper balance of our projects' scientific capabilities, budgets and schedules. Over the past decade, the worldwide HEP community has come to realize that another concern must be added to this balancing act: the direct impacts that our activities have on the communities and environment in which we exist. This means that we must plan to limit the specific and sometimes unique impacts that our collaborative projects and individual work have on the climate and broader environment. These and other aspects of internal HEP community engagement resulted in the formation of many specific recommendations for changes or improvements within our field, all of which can be found in the various CEF Topical Group Reports. Overlaps and relationships that exist among the inward-directed recommendation of each Topical Group led to the development of the following goals for engagement within the HEP community (each referenced by the Topical Groups whose reports most directly relate to that goal).

- **The HEP community should institute a broad array of practices and programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision. In particular, we need to encourage stronger participation in HEP collaborations by faculty and students from non-R1 academic institutions. (CEF02: Section 3.3; CEF03: Section 3.4; CEF04: Section 3.5)**

- **HEP communities are still plagued by the alienation experienced by marginalized physicists who are part of the community. HEP needs to address these persistent issues by employing the use of robust strategic planning procedures including a full re-envisioning of our workplace norms and culture to prioritize eliminating the barriers and negative experiences faced by our marginalized colleagues. (CEF03: Section 3.4)**

  - **Research institutes and universities should do more to maintain the highest standard in work-life balance and mental health of staff. Proper training of staff should be developed to integrate productive work habits that encourage a balance between professional expectations and private affairs, and good mental health. (CEF02: Section 3.3; CEF03: Section 3.4; CEF04: Section 3.5)**

- **The HEP community needs to address under-representation of many groups within the field by implementing new modes of community organization and decision-making procedures that promote agency and leadership from all stakeholders within the scientific community. (CEF03: Section 3.4)**

  - **Funding agencies, Universities, laboratories, and HEP groups should improve and sustain international outreach, partnerships, schools, workshops, conferences, training, short-visits for research, and development of research consortia; mechanisms should be developed to facilitate the participation of colleagues from developing countries. (CEF03: Section 3.4)**

- **In addressing the unique needs and issues of marginalized physicists, HEP communities must engage in partnership with scholars, professionals, and other experts in several**

disciplines, including but not limited to anti-racism, critical race theory, and social science. (CEF03: Section 3.4)

- **All HEP communities should create structures to fully open career path opportunities to everyone, and to conduct event planning to ensure events are accessible to all community members, especially those with disabilities. (CEF03: Section 3.4)**
- **The HEP community should enact structural changes to foster broader, deeper, and more effective participation in community engagement, through policies such as considering community engagement work in hiring, promotion, and grant decisions. (CEF05: Section 3.6, et.al.)**
  - **Individual scientists should encourage others, including peers, mentees, and students, by participating in public engagement and discussing its importance. (CEF05: Section 3.6)**
- **HEP needs to improve communication channels with the funding agencies and internal communication within HEP concerning program planning and funding, particularly with regard to the upcoming P5 plan. (CEF06: Section 3.7)**
- **HEP must take greater responsibility for its impacts on climate change by addressing and mitigating these impacts through DOE project policies and individual community member actions. (CEF07: Section 3.8)**

Education

Professionals in particle physics must be prepared for careers in the field through instruction in the skills, techniques and investigation processes characteristic of the discipline. This training primarily occurs within the education community spanning kindergarten through postdoc (K-PD). The development of foundational skills and interests must begin in early grades of local schools, and should eventually expand to include learning experiences in international settings. To produce colleagues with the specific abilities required for modern HEP research, our academic institutions need to be teaching content that matches the needs of our discipline. However, US universities for example, are sometimes towers of tradition, slow to adapt to changing career environments, especially when people active in the fields do not communicate the needs for change.

One particular area of disconnect is the trend that has developed of US HEP becoming a more specialized pursuit, weighted more and more heavily toward the academic, analytical side of the work. With changing dynamics in the organization and funding of HEP within the US, many HEP individuals and collaborations have less familiarity with the technical or engineering expertise required for our projects. In addition, modern particle physics analysis depends on the application of specific skills that are not often part of the standard degree programs in many universities. These can range from tried-and-true statistics that are often learned "on-the-job" in our field, to more novel disciplines such as Artificial Intelligence algorithms that are becoming increasingly common in our work.

These concerns along with needs to improve connections with K-12 and international students are reflected in goals for HEP engagement with the Education community, formulated to address educational deficiencies specific to our field.

- **Our field cannot absorb all the early career members that it produces, so funding agencies, national laboratories and universities should work together to provide more education**

and career opportunities for engineering and industry-focused research within and outside HEP, and update degree programs to match better the skills needed and career opportunities required in today's HEP and related fields. (CEF01: Section 3.2; CEF02: Section 3.3; CEF04: Section 3.5)

- **HEP academia should work with K-12 teachers and students to create supportive local communities to nurture student interest in math and science. (CEF04: Section 3.5)**
- **Pre-university and university programs for international student collaboration need to be expanded and supported, especially to partner with colleagues in developing countries. (CEF04: Section 3.5)**

Industry

In times past, the US HEP community was supported by strong direct relationships with vibrant industries well matched to the technological needs of the field. Over the years, as modes of project management, funding, licensing etc. have evolved, it has become increasingly difficult for US HEP to provide support through project partnerships adequate to support a viable industrial base of US companies capable of providing the technology production required for successful execution of HEP projects. Often, these mutually beneficial two-way relationships remain stronger in Europe and Asia than they do in the US. For example, industrial accelerator companies in the US represent a rather small community.

Improvements in HEP-industry relationships can be achieved at all scales. HEP could strengthen relationships with large microelectronic firms through new models of agency- or field-wide licenses and platform access. Partnerships with smaller startup companies often exist and are much easier to nurture at the lab or university level, so those connections should be leveraged. From the industry perspective, the reduction of cross-agency or cross-office barriers will enhance and accelerate innovation.

Many of the proposals envisioned for promoting strong relationships between the Industry community and HEP are represented in the following overarching goals for Industry engagement.

- **Funding agencies and the national laboratories should enhance policies and programs to promote a more fertile environment for cross-agency technology development and technology transfer, and to support co-development of specific technologies with industries such as accelerators, microelectronics, and FLASH-RT. (CEF01: Section 3.2; CEF02: Section 3.3)**
- **Together, laboratories and universities need to help bolster our US industrial support base by pursuing targeted partnerships with early stage scaleup companies on HEP projects. (CEF01: Section 3.2)**
- **The HEP community needs to strengthen ties with industry and other fields by developing effective alumni networking tools and programs, to facilitate transitions to industry careers and encourage industry collaboration on HEP projects. (CEF02: Section 3.3)**

Policy

When we speak of Policy in this context, we do not refer to the official rules themselves by which an organization operates. We refer to a specific target community for HEP engagement. That is the Policy

community, or collection of various governments and individuals working within government that have influence on enacted policies that directly affect our field. HEP, Education, and Industry communities all operate and exist within a milieu of government policy.

The core of HEP's Policy engagement has always been its highly effective Congressional advocacy, conducted by the major Users groups representing US particle physics to secure strong funding for US HEP. The primary component of that Congressional advocacy is the "DC Trip," which has been developed, expanded and refined by a small group of dedicated colleagues for decades. It has become a major sophisticated operation that is held up to other fields as the gold standard of scientific advocacy. Throughout the P5 era, HEP has successfully garnered strong bipartisan support in Congress for the field's program of research. One weakness of this effort is the wholly volunteer nature of the stewardship of our Congressional advocacy. The HEP community should dedicate resources to put it on a sustainable path for future growth.

On the other hand, there is considerable room for improvement in our advocacy to the federal Executive branch. Across most administrations, support for HEP in Presidential budget proposals has typically not reached the level of Congressional support for many years. Our interactions with the Executive branch are limited in breadth and frequency, so this is a potential area of significant growth. The HEP community has rarely, if ever, mounted any real effort to advocate on behalf of the field to state or local government. While state and local advocacy would likely be selective in its application, it still represents a real growth opportunity for HEP support.

Colleagues have expressed interest in advocating for non-HEP funding issues that may not be HEP-specific, but have direct impact on our field and its health. Examples include issues such as VISA and immigration policy. The Users group Congressional advocacy has never directly promoted policies outside of HEP funding, and likely would not attempt to advocate for non-HEP-specific issues on its own. The main reason being the general principle that advocacy is best carried out by the largest group available with common purpose on a given issue. Therefore, partnership with broader scientific societies such as APS, AAAS, etc., would be a more powerful form of HEP advocacy for more general scientific issues.

Consequently, the greatest growth in HEP Policy engagement would be achieved by achieving the following overall goals.

- **APS DPF, HEPAP, and the user groups need to review the structure of HEP advocacy, including considering the formation of an HEP community government engagement group with responsibility for expanding government engagement capabilities. (CEF06: Section 3.7)**
- **The HEP user groups and DPF need to provide the resources for continued growth and sustainability of the annual HEP Congressional advocacy effort. (CEF06: Section 3.7)**
- **The users groups, DPF, laboratories and universities should build on our successful HEP Congressional advocacy by expanding our advocacy to the federal executive branch and state and local governments. (CEF06: Section 3.7)**
- **HEP should establish a group in partnership with other science and physics societies on advocacy for non-HEP funding issues. (CEF06: Section 3.7)**

Society

Each of the four target communities described above are subsets of the broader society at large, existing within what is sometimes referred to as the general public. When we speak of broader society as a target

community for engagement, typically we are referring to the portion of society that is the complement of the union of the other four communities. In other words, everyone in society outside of HEP, Education, Industry, and Policy.

The key theme in Societal engagement is reflected in the term engagement itself. Until recently, interactions with the public were usually spoken of as Public Outreach. However, outreach implies reaching out to some group. In other words, it is a one-way activity between groups that are not on the same level. HEP is telling other people something. What we're saying might be good, but we're not listening. This is not an effective means of building relationships. Conversely, most groups involved in outreach communication have evolved to frame what they do as engagement, or engaging with another group. This implies a co-equal partnership, hopefully one that is mutually beneficial.

This value leads to the articulation of two major goals for real community engagement with the broader society, one very general, and one very specific.

- **HEP needs to transition from an ethos of conducting outreach and communication to the public, to a culture of engagement in relationships with the public. This should be done by building lasting relationships with the full breadth of all of our supporting communities (especially those that have been historically excluded) that are not based on transactional interactions, but rather real two-way partnerships that consider the needs and interests of the audience and include its members in program design. (CEF05: Sections 3.6; CEF07: Section 3.8)**
- **HEP should build synergistic collaborations with the non-proliferation community that draw on a broader spectrum of funding sources for work on HEP-specific technologies related to nuclear non-proliferation. (CEF07: Section 3.8)**

3.1.2 Participation and Implementation

Throughout the Snowmass 2021 process, there has been relatively low participation in Community Engagement Frontier efforts. This is true although it is generally agreed that CEF topics are cross cutting, i.e. they affect the entire community to various degrees, and thus are important to be addressed. The vast majority of CEF work was carried out by the small number of frontier and topical group conveners, with only a few additional dedicated community members making significant contributions. Indeed, many contributed paper study groups were led and conducted by the CEF topical group conveners themselves through to publications of these papers, because of low community involvement. Instead of CEF being a cross-cutting frontier with significant participation, it became an isolated set of activities—in spite of frontier liaisons—carried out by a relatively small group of people; almost all of whom are also physicists with interest in the other "physics" frontiers. These dedicated volunteers were largely prevented from participating in the Snowmass physics frontiers at significant levels due to the burden placed on them by the lack of participation in CEF by the majority of their HEP colleagues. As a result, all of the CEF topical group conveners sacrificed career advancement opportunities in order to carry out the work necessary for the health of the field on behalf of the entire HEP community. Various reasons have been suggested to explain low involvement in CEF, e.g. lack of time or the fact that career progression depends on the quality of research output rather than community engagement effort. Surveys done in Refs. [6,9] offer further insights into the low participation issue. It is also possible that Snowmass is the wrong time for the community to focus on developing a plan for addressing CEF issues. Certainly, individuals' concerns for time management and maximizing the potential for career development are heightened during the high-stakes planning and decision-making of Snowmass. Snowmass

may be the one time that presents the greatest barriers to a large fraction of the community choosing to participate in CEF, so perhaps this should be the last time that CEF is a part of Snowmass. *Whatever the reasons, the HEP community both corporately through structural change and as individuals through personal reflection must decide that everyone's participation in CEF issues is required for the field to become healthy and grow. We can no longer rely on a small number of colleagues to shoulder the full burden of this work to the detriment of their own careers. Our field simply will not survive otherwise.*

If the field of HEP does decide that CEF issues are worth addressing, and furthermore commit to doing so, then a plan of implementation of CEF recommendations must be developed. In the past, the responsibility for guiding the selection and implementation of Snowmass recommendations has been wholly delegated to the Particle Physics Project Prioritization Panel (P5). This arrangement has worked exceedingly well over the last 8 years for implementing a consensus plan of HEP projects. However, experience has shown that the current P5 mandate and makeup is not suited to adequately shepherd other areas of the HEP enterprise, including community engagement issues. For example, Snowmass 2013 included the Community, Education, and Outreach Frontier, which produced a report that made several recommendations [1]. Neither P5 nor any other HEP organization or leaders took ownership of those issues to ensure that recommendations from that frontier were implemented. As a result, despite the fact that individual people and institutions in our community have made efforts in these areas in the last decade, little overall progress on these recommendations has been realized since the last Snowmass.

To avoid a similar fate for Snowmass 2021 CEF recommendations, US HEP must establish a structure by which designated entities are given ownership of and responsibility for ensuring that CEF recommendations are implemented and monitored for progress. One such possibility is simply expanding the P5 charge to encompass CEF issues. It is not clear that is the most appropriate solution, though. P5 was explicitly designed to effectively prioritize (largely experimental) HEP projects. It may be that P5 is not ideally situated in the HEP ecosystem, or appropriately staffed to evaluate, choose, and monitor the progress of CEF initiatives. Considering the five engaged communities around which the CEF goals are organized, it could be that the American Physical Society Division of Particle and Fields (DPF) is best positioned to shepherd the internally-focused recommendations for HEP because that organization is most representative of the entire field's membership. Perhaps a group formed in partnership between the funding agencies, the laboratories, and universities is needed to manage engagements with industry since that is where most of the direct relationships with industry are formed. Universities Research Association's membership consisting of university administrations and its role in connecting academia with laboratories could make it best suited as a sponsoring organization for a team to work towards implementation of education initiatives. An option of forming an HEP community government engagement group, composed of elected community representatives and policy experts, to expand advocacy efforts, should be considered. As the focal points for public engagement with HEP, the laboratories themselves may be the ideal choice to manage the recommended programs directed at the broader society. *All of these stakeholders should begin the conversation that must lead to an agreed upon structure for taking responsibility for implementing CEF recommendations. If this does not happen, then we face another decade of no progress on CEF issues in the HEP community.*

The rest of this report describes the impressive amount of high-quality work that a small number of your colleagues accomplished on your behalf. We hope that as you read and consider this content you will be convinced of two propositions:

1. **It is critical that we as individuals agree on the importance of all working together to address CEF issues in HEP.**

2. **A structure within HEP for taking ownership and responsibility for implementing CEF recommendations and monitoring their progress must be developed.**

If we as a field can make these two ideas a reality, then US HEP will be much stronger and healthier by the time we gather for the next Snowmass process.

3.2 CEF01: Applications and Industry

The charge for the topical group CEF01: Applications and Industry is to develop strategies to strengthen HEP/Industry relationships in both directions, i.e. forming more partnerships to draw on industry expertise to further HEP goals and building on programs to facilitate transfer of HEP technologies/techniques for use in the broader society. This group considered the relationship between HEP laboratories, universities, and industrial stakeholders. In particular, CEF01 pursued the following objectives: (1) how to create an innovation ecosystem mutually beneficial to national laboratories, academia, and industry, (2) how to maximize the HEP-funded technology outcomes benefit to practical applications, (3) how to encourage co-development of related applications across agencies and programs, and (4) how to leverage HEP project partnerships to enable innovators to become entrepreneurs through tech commercialization.

In order to expand the discovery reach of experimental high energy physics, innovations in a variety of technologies are required to push operational and measurement tools and techniques to ever-higher levels of spatial and temporal precision. Not only do these advances propel scientific discovery, but they also enhance industrial capabilities to deliver novel and powerful applications to the benefit of the broader society. Strong development relationships between laboratories and universities of the HEP community and small to large scale tech companies in the industrial community are key for building an efficient and sustainable ecosystem for advancing technologies such as accelerators, microelectronics, artificial intelligence, and quantum information.

With individual modern HEP experiments characterized by industrial scales such as detectors with more than 1 billion sensors, 70 kilotons of liquid argon, or data rates equivalent to the entire North American internet traffic, it is obvious that a robust and diverse array of industry partners is necessary for HEP to mount almost any project in its portfolio. On the other hand, the engineering design benchmarks needed to handle the extreme radiation, cryogenic, low power, and inaccessible operating environments of HEP projects often exceed those typically found in industry by orders of magnitude. Multidisciplinary technology design and production partnerships for HEP between national labs, academia, and industry accelerates lab to fab innovation, prototyping to scale, technology maturation, spin-off development, and rapid adoption, all of which benefits industry capabilities; it also accelerates scientific discovery across the landscape of federally-funded research.

Barriers to effective HEP-Industry partnerships do exist. Although Small Business Innovation and Research (SBIR) funding can facilitate lab and university partnerships with small business, SBIR timeframes and funding levels are inadequate to support the large-scale HEP projects that require collaboration with big business. HEP technology goals and requirements are often not communicated to industry broadly and effectively. Economy of scale with regard to tool and license purchases from industry is typically not exploited in HEP. Science goals are not well-mapped to technology goals across funding agency offices, often resulting in the loss of synergistic co-development opportunities.

Those working in CEF01 produced five contributed papers examining three different modes of collaborative partnership, and cooperation on three different specific areas of technology:

- Programs enabling deep technology transfer from national labs [10];
- Application-driven engagement with universities, synergies with other funding agencies [11];

- Big industry engagement to benefit HEP: microelectronics support from large CAD companies [12];
- Transformative technology for FLASH radiation therapy [13];
- Nurturing the industrial accelerator technology base in the US [14];

The following sections summarize the ideas and set forth the suggestions arising from each of those papers, and detailed in Ref. [2].

3.2.1 Programs Enabling Deep Tech Transfer from National Labs

To achieve the scientific goals of HEP projects, DOE national laboratories and the experiments they host require innovative ideas and at-scale prototyping for novel technologies. These projects must bridge the academy's drive to push beyond state-of-the-art capabilities to industry's forte in quality control and reliability. Experiments and industry collaborating to move these novel technologies from ideas to robust and cost-effective mid-scale manufacturing, can put industry on a path to commercial production. However, a proper environment is necessary to nurture this laboratory to fabrication (or lab to fab) technology transfer process in a manner that can sustain spin-off development and startup ventures over the long term. Several recommendations are made to develop an effective technology transfer ecosystem or for HEP at the national labs:

- **DOE should implement specific policy changes to foster deep technology transfer. (CEF01 Recommendation 4)**

  There are several specific policies within DOE that could be optimized to encourage more efficient technology transfer. Aligning inventor royalty distribution consistently across the DOE complex would simplify commercialization of technology developments. Laboratory and/or Division royalty shares might be used to support additional projects, rewards programs, and innovation/entrepreneurship educational opportunities for laboratory staff.

  The use of Partnership Intermediaries (PI) can accelerate commercialization, particularly for laboratories supporting HEP facilities with limited Technology Transfer (TT) resources. A PI is a non-profit with specialized skills to assist federal agencies and laboratories in TT and commercialization. Past pilot programs in the Department of Energy Office of Technology Transitions have shown promise in assessing technologies for market pull, marketing HEP-related technologies, and matchmaking technologies at national labs with entrepreneurs in private industry. This can be particularly successful by identifying "dual-use" applications early, which can be leveraged to enable upfront marketplace analysis and speed market acceptance.

  Other Transaction Authority (OTA) is a special mechanism federal agencies use to obtain or advance R&D or prototypes. The government's procurement regulations and certain procurement statutes do not apply to OTs; thus, OTA gives agencies flexibility to develop agreements tailored to a particular engagement with companies unwilling or unable to comply with the government's procurement regulations. While the Energy Policy Act of 2005 granted OTA to DOE at the agency level, it did not authorize the labs to use it directly. OTA could be a more effective model for technology transition if driven at the local laboratory level, where the interaction with industry is vital for success.

- **Industry and national laboratories should develop public-private partnerships to accelerate scientific discovery and benefit industry applications, particularly in emerging technologies. (CEF01 Recommendation 1)**

  Promoting public-private partnerships will accelerate HEP innovations. In specific technology areas such as accelerators, US federal program managers proposed developing public-private partnerships to foster and support small and large technology businesses who collaborate with the laboratories and serve as commercialization partners for critical technologies developed as part of facilities and experiments in high-energy physics. These public-private partnerships could serve as both advocacy and economic development entities for HEP-derived technologies, as well as matchmakers that aid companies and laboratories in forming collaborations, which lead to positive commercialization outcomes.

  Entrepreneurial Leave Programs (ELP) allow employees to take a leave of absence or separation from the laboratory in order to start or join a new private company. ELPs encourage startup activities by reducing the risks faced by the employee entrepreneur. Some elements of an ELP may include business preparation/training, a means for licensing laboratory IP, continuity of health benefits during leave, and a mechanism for returning to work. ELPs are not implemented consistently across the DOE complex; some laboratories have ELPs while others do not.

  Providing more technology transfer educational opportunities targeted to HEP researchers will facilitate a ramp-up to I-Corps level of engagement for high-energy physics researchers. This would be a great opportunity to provide researchers the building blocks to enable more engagement in capturing innovations. Discussions on the types of intellectual property (ex. patents, copyrights), rights afforded to researchers from their innovations, and the mechanisms to engage with industry to advance their technologies would provide valuable resources and new perspectives to HEP personnel.

3.2.2 Technology transfer with Scaleups

HEP collaboration with small businesses is primarily facilitated through SBIR program Phase I awards, which are relatively plentiful I and easy to access. However sustaining development through this channel is difficult because Phase II awards are more limited in number and lack sufficient funding for deep tech transfer. Work with large companies through Cooperative Research and Development Agreements (CRADA) is a slow and lengthy process. In the long term, CRADA partnerships are quite fruitful, but the slow starts and small number of opportunities create a high barrier for execution.

A relatively unexploited and overlooked intermediate option is partnership with mid-sized scaleup companies in the post-startup phase. These middle-ground businesses can be identified using a bottom-up approach of scouring online databases such as crunchbase.com and dealroom.com. A top-down approach of building relationships with venture capitalists (VC) with vested interests in scaleup firms.

- **HEP should leverage multiple programs and relationships to build collaborations with scaleup companies on HEP projects.**

  Laboratories should host "Discovery Days" for scaleups. National laboratory business development (BD) efforts with larger companies involve hosting Discovery Days. Product leads and problem owners from companies are invited to visit the lab and have discussions with

technical/domain experts. Success is measured in the number of Discovery Days that convert to project collaborations. Similar Discovery Days to host scaleups at the lab to deep dive into their technology roadmap need to be established.

Venture Capital firms generally prefer to procure services from a commercial service provider instead of a lab, partly because of the relative difficulty getting technology out of the lab due to how hard it is to get an exclusive license. Labs find it better to give exclusive license to large corporations, as opposed to startups where there is more chance the company might fail. Leveraging contacts at venture capital firms is extremely useful, since they have access to service providers such as lawyers, accountants, government lobbyists, and labs. The labs create a summary description of what they do (i.e. their value proposition), which VCs can then share with companies to see if they are interested.

HEP should also leverage existing university relationships to connect with Venture Capitalists. Some VCs such as ARCH look for strong scientific founders who can help their companies at early stages including getting an exclusive license from the university, which is not as easy to get from a national lab. The university model, which allows staff members to spend one day a week on external projects, helps facilitate such work.

3.2.3 Application-driven engagement with universities, synergies with other funding agencies

Laboratory-university HEP partnerships have been very successful, but within the United States have been limited to university physics departments. However, as technology advances, the level of engineering design for accelerators and detectors keeps growing and close collaboration between the labs and university engineering departments is becoming more important. Interactions between the labs and engineering departments are opportunistic and transactional rather than systematic and synergistic like with physics departments. In contrast to Europe, the US HEP community does not have the programmatic ability to directly support application engineering research in the academy. In areas such as computation and microelectronics, upcoming HEP technology projects will require significant amounts of engineering R&D. This activity and those conducting it need to be considered integral to the HEP community. In addition, HEP labs need to partner with universities to produce a technology workforce.

- **Funding agencies should work with universities to create cross-agency engineering initiatives focused on application-driven fundamental technology rather than fundamental science. (CEF01 Recommendation 3)**

  The DOE Office of HEP should engage more with engineering departments to create explicit representation of engineering partnerships in established listings of funding opportunities. Clearly label support for HEP-Engineering efforts, such as fellowships reserved for engineering graduate students, or a class of projects designated as science-engineering partnerships, where the project application requires dedicated components reserved for both science and engineering (similar to NSF grant funding where a research and an education component are requested to be described individually). These engineering collaborations should be expanded across DOE and with other agencies (e.g. NASA, NSF, DOD).

- **HEP labs and universities should work together to develop intentional pipelines of engineers for the HEP workforce from undergraduate students to professional ranks.**

A possible pipeline could be as follows. HEP labs recruit undergrads for internships through partner universities → students are trained in the setups and topics the HEP lab prioritizes → successful undergraduate students are channeled to graduate programs across a network of partner universities → universities recruit these students into engineering PhD programs → co-advising models are used to mentor these students by both an engineering professor and a HEP scientist → feed the students back into the HEP workforce.

In addition, universities should welcome input from HEP labs on recruiting the next generation of graduate students from the cohort of international students with interdisciplinary (physics, science, and engineering) backgrounds. Schools could also establish joint academic appointments for HEP lab and industry scientists within engineering departments. These HEP scientists could then also be thesis advisors and thesis committee members of students.

HEP labs should promote engineering students for awards, such as the URA Visiting Scholar award. Often times, engineering faculty and engineering PhD students are not aware of all opportunities that exist within the HEP and national lab ecosystems. Guidance from HEP scientists will help lift entry barriers for them.

3.2.4 Big Industry Engagement to Benefit HEP: Microelectronics Support from Large CAD Companies

Only a few large companies have both deep expertise in modern microelectronics and access to CAD-EDA tools. In addition, ASICS designed for the extreme environment requirements characteristic of HEP have little market value for those large companies. Therefore, microelectronics for HEP tend to be designed by partnerships of national lab and university personnel. However, these collaborations typically do not have access to the suite of CAD tools due to complicated and expensive licensing frameworks, which are negotiated independently by each DOE lab. The DOE needs to develop a centralized licensing framework with CAD vendors to bring economy of scale and flexibility for each lab to procure the set of tools required for their own projects and teams. There are motivating benefits to the microelectronic industry to pursue this business relationship with HEP. Extreme environment microelectronics make up little of the commercial market, but that segment is growing, particularly for QI and AI applications. DOE science users are typically good sources of feedback on cutting edge uses of advanced CAD-EAD tools, and also develop the talent pool for the microelectronics workforce. The following recommendations arose from DOE HEP hosted meetings with several major CAD-EAD companies.

- **A collective all-of-DOE approach for engaging Big Industry should be employed for procurement of common industry tools, licenses and services. (CEF01 Recommendation 5)**

  Setting DOE-wide common terms and conditions with the flexibility for each lab to make the technical choices specific to their program and negotiating low-cost research licenses for basic science developments will enhance project collaboration with big companies. DOE should consider creating a Collaborative Innovation Hub scoped for cooperative team shared access to CAD/EDA tools, training, and support. Establishing dedicated cloud-based communal participation platform between academia, DOE national labs, and CAD/EDA companies, and leveraging successful solution frameworks (e.g. DARPA Innovation Package, Europractice IC Service, DOD Cloud Access Rights) will bring efficiencies of shared access.

It will also be useful to Incorporate some aspects of CAD/EDA companies' academia policies for research projects at national labs, in order to create a new class of research licenses. The resulting solutions should keep intact the premise of CAD/EDA companies' contributions with special arrangements for commercializing research results. The academic network can also be leveraged to cultivate the talent to advance and promote innovations in semiconductor technologies.

3.2.5 Transformative Technology for FLASH Radiation Therapy

Radiation therapy (RT) cancer treatment has arguably delivered the greatest societal impact of any particle accelerator application, and a large share of accelerator science has been enabled through HEP research support. FLASH radiation therapy (FLASH-RT) is a recent development in which ultra-high doses of therapeutic radiation are delivered in less than a second. Experiments show that FLASH-RT effectively destroying tumors while almost completely sparing normal tissue. However, there are technical difficulties in the development of a clinically-safe delivery system, and the accelerator capabilities within the HEP community will be needed to resolve the issues.

Most R&D for FLASH has been carried out using 4-6 MeV electrons from clinical linacs, producing strong results. Photon beam FLASH studies using synchrotron radiation and X-ray tubes have yielded mixed results. Some work has also been done with 230-250 MeV shoot-through beam protons from CW and iso-cyclotrons. Limitations include intensity requirements preventing the use of energy degraders for proton beams, and synchrotrons lacking the intensity of ion beams required for FLASH.

- **Prioritize and simplify high risk, high reward transformative technology opportunities. (CEF01 Recommendation 6)**

  In some technical areas (e.g. FLASH radiotherapy), high impact technology incubation by the HEP ecosystem can produce significant, and occasionally disruptive, benefits to society, within a decade timeframe. In these scenarios, we recommend prioritizing and simpliying access by all domestic stakeholders to HEP facilities, expertise, and resources.

  The HEP community should carry out a broad R&D program to clinically realize the curative potential of FLASH-RT with different radiation modalities. Among the relevant projects are:

  - The Advanced Compact Carbon Ion Linac (ACCIL) is a program initiated by the Argonne National Laboratory to develop up to 1 kHz repetition rate, compact proton linac capable to deliver FLASH-RT doses.;
  - Scaling Fixed Field Gradient Accelerators (FFGA) are synchro-cyclotron style proton accelerators, which can operate at high repetition rates and high currents consistent with FLASH needs; most of the current R&D programs on scaling FFGAs are performed by Japanese research groups.;
  - Non-scaling FFGAs are particularly well suited for accelerating other ion species (i.e. carbon), and there is a pilot facility under construction at the National Particle Beam Therapy Center (Waco, TX).;
  - Laser-driven accelerators can deliver very large doses of protons or high energy electrons from a compact source (both scenarios are potentially of interest to FLASH-RT). The bulk of US program is centered at the LBNL BELLA laboratory.;

- The pulsed power based linear induction accelerator (LIA) using a multilayered bremsstrahlung conversion target also represent very promising technology in meeting FLASH-RT requirements, and there is a pilot program underway at LLNL.;
- Multiple groups are also working to develop FLASH-capable X-ray systems, including the ROAD initiative by UCLA/RadiaBeam, and PHASER initiative by SLAC/Tibaray.;
- One potential application, which can take advantage of the recent interest by HEP community towards novel cold RF technology, is a compact cold-RF Very High Energy Electron (VHEE) radiotherapy system, with relevant R&D programs initiated at SLAC and at CERN.;

3.2.6 Nurturing the Industrial Accelerator Technology Base in the US

It is widely perceived by the HEP accelerator community that accelerator technology transfer to US industry is not a high priority. US HEP commonly develops state-of-the-art accelerator technology, then buys it back later from international firms for domestic projects. Europe and Asia have nurtured vibrant accelerator industrial bases, leaving US firms at a competitive disadvantage. This has resulted in a US accelerator community plagued by increased costs, insufficient component availability, dependence on foreign sources, small talent pool of technical personnel and low societal recognition of accelerator science benefits.

Although industrial firms play critical roles in the scientific enterprise, important US accelerator companies have struggled to survive. Pioneers in SCRF and undulator technology enjoyed initial success, but failed due to the inability to sustain support from DOE research, leading to the loss of capital and unique expertise. Regulatory and policy recommendations are suggested to build a competitive domestic industrial base for accelerator technology.

- **DOE should invest in programs to provide direct support to specific critical need industries. (CEF01 Recommendation 7)**

  There is a growing interest in the community to improve support to the domestic industrial vendors providing critical technological capabilities to the HEP ecosystem. We recommend that DOE takes a proactive approach in establishing critical technology needs, and work directly with the qualified vendors to maintain and develop critical industrial capabilities, relevant to these needs.

  Modify the US Small Business Innovation Research (SBIR/STTR) program to nurture these small businesses across the "Valley of Death". One improvement would be to more closely align the program technical topics to the future procurement needs of the labs, and encourage the labs benefiting from the SBIR funded work to maintain the momentum and work with the industry beyond the SBIR funded phase. DOE should also establish a method to identify key technologies that will be needed in a decade time frame and create new channels of direct funding to the qualified industrial enterprises to develop expertise, infrastructure, and capacity to meet such needs. It is also equally important to be able to help sustain the companies that have already achieved critical capabilities.

  Support specialized industrial vendors by implementing directed "knowledge transfer" programs. Recent decades saw a proliferation of national laboratories-based commercialization centers built around the technology transfer activities. Yet, few of them can report success and the idea of technology transfer through funding the commercialization activities by the labs is generally

counterproductive for the purposes of building the industrial vendors base. We believe it would be more beneficial to deemphasize technology transfer as a means of supporting the labs, and emphasize knowledge transfer as a means of supporting motivated businesses to expand capabilities of interest to the DOE programs.

Laboratories should also simplify some of the procurement practices, and likewise explore various creative ways for industry and laboratories to collaborate on the prototype developments that would minimize the risks and maximize return to both sides. The accelerator community should promote programs that facilitate direct and open communication channels between laboratory engineering and technical staff with their industrial counterparts (there are many conferences for scientists to attend and share their experiences, but not so many venues are available to technicians and engineers whose skills are essential and irreplaceable in our field).

3.3 CEF02: Career Pipeline and Development

This working group is not simply about making early career scientists aware of different opportunities, but also changing the culture of HEP career paths. It aims to identify and encourage career opportunities for high energy physicists in both academia and industry, and to identify useful partnership options between HEP and industry. Smoother pipelines between different types of employment are critical for the success of HEP trainees in the future. One objective is to promote the skill development of physics graduates and young researchers and encourage career direction-based scientific majors and skills.

Thirty-two LOI were submitted to this working group and were condensed into three contributed paper topics, namely:

1. Facilitating Non-HEP Career Transition;
2. Enhancing HEP research in predominantly undergraduate institutions and community colleges;
3. Tackling diversity and inclusivness in HEP.

Topic (3) was integrated to and developed in the topical group on diversity, equity and inclusion in Section 3.4. Ultimately, two contributed papers on topics (1) and (2) were prepared and presented in Refs. [15, 16]. Considering that there are fewer academic positions than job seekers, many degree holders will eventually seek jobs outside HEP, where, in sectors such as industry, there are demands for skills acquired in HEP training, e.g. data science or machine learning. However, organized guidance—developed through engagements between the HEP community and the alumni that have already transited out of HEP—is needed to help with non-HEP career transitions [15]. Another career trajectory may to employments at predominantly undergraduate institutions (PUI) and community colleges (CC), with high teaching loads and lack of support for research. PUI and CC can serve as pipelines to improve diversity and under-representation in HEP, by facilitating participation of faculties and students at PUI and CC in HEP activities [16].

3.3.1 Facilitating Non-HEP Career Transitions

It is noted in Section 2 of Ref. [15] that more that two-third of trained physicists will eventually transitions to employments in private or government sectors, collectively referred to as "industry"; moves to the industry sector may occur at various stages of HEP career evolution and proper planning is needed to facilitate the

transition. A survey conducted by the Snowmass Early Career (SEC) physicists included questions about career pipeline and development [9], to offer insights on existing efforts, support, networking, preparation and attitude towards career change and alumni participation or eventual return to HEP. Details about the SEC survey and findings related to career pipelines and development are documented in Refs. [9, 15]. We recall here the suggestions:

- Supervisors and mentors should be directly involved in planning the career of their mentees early on. This career plan should not be based on the desires of the mentor but the skills and interest of the mentee. A commensurate effort in the job search process is also needed.
- Supervisors should allow a certain fraction of working time for their mentees to pursue opportunities and preparation activities for a possible industry career.
- HEP experiments, laboratories, or university departments should provide training for supervisors so that they can better understand and be more sensitive to the needs of their mentees in terms of their career goals and preparation.
- HEP experiments and/or laboratories should provide workshops on industry job preparation: translating HEP skills and examples to industry language, converting CVs to resumes suitable for different fields, finding successful job search phrases (for example, "Engineer" or "Data Scientist" as opposed to "Physicist"). This will be most successful when paired with the recommendations below for deepening connections with HEP alumni.
- HEP experiments and/or laboratories should develop innovative opportunities for networking with HEP alumni in various fields to strengthen industry job search success. Alumni are more than willing and happy to respond and engage. This will be most successful when paired with the recommendations below for deepening connections with HEP alumni.

The survey revealed that about 50% of respondents tried to find jobs in their field before moving on to opportunities in industry; they exited at student or post-doctoral levels and went to STEM-related responsibilities outside academia. These transitions were mostly facilitated through networking; but the difficult step is to leave at a relatively late stage in academic. It is challenging to return to HEP but alumni are open to joint projects, and this can help strengthen partnerships between HEP and industry [15]:

- Supervisors and mentors should actively communicate with alumni and highlight their experiences for current students and postdocs, to normalize the reality of transitioning to an industry career.
- The US HEP community should develop tools and portals for connecting with alumni. Existing programs for networking with alumni like at CERN must be studied and adapted. This effort should be supported and strengthened by funding agencies by dedicating a small amount of continuous funding to support technical and personnel staff that can organise and build a framework that can serve as a hub to facilitate process of networking with alumni. A DOE lab would be an ideal place to host this effort, like Fermilab, which is a hub for US particle physics.

HEP experiments and laboratories should take creative steps to reverse "brain drain" from HEP by exploring mechanisms for collaboration with alumni on HEP projects:

- Alumni are a relatively low cost but very valuable asset with an abundance of experience from transitioning to an industry career. Their goodwill to contribute and strengthen ties with HEP can be tapped to facilitate industry job transitions and further the goals of both groups.

- Individual scientific collaboration can be extended to the company of the alumni itself and this can strengthen knowledge transfer from labs and universities and vice versa; and work done by HEP research can benefit companies and vice versa.

HEP training offered at universities and laboratories could be extended to industry for opportunities to apply HEP skills in a different environment and culture and this may facilitate eventual career transitions. The survey showed support to develop such HEP-industry partnerships [15]:

- HEP laboratories should create targeted internships or training programs in the areas of Accelerator Technology, Computer and Information Science, Detector and Engineering Technology, Environmental Safety and Health and Radiation Therapies. This would expand access to industry-focused training to students and postdocs who are not based at national laboratories.
- HEP laboratories should leverage existing public-private partnerships with industries like Accelerator Technologies, Computers Information Science, Detector and Engineering Technologies and also Environmental Safety to create experience for resident students and early career scientists to build skills ad connections for a future industry career.
- Funding agencies should evaluate funding rules and regulations to allow HEP students and postdocs to pursue industry-focused training that can be integrated with their core research curriculum.
- Supervisors must adopt a mindset that industry partnerships and career transitions are valuable options for their students and postdocs, and should support their participation in training opportunities whenever possible.

3.3.2 Enhancing HEP research in predominantly under-graduate institutions and community colleges

HEP activities are carried out primarily by people at laboratories and research focused non-PUI. However, about 40% of undergraduate students in the United States are enrolled in CC where ∼80% are from demographics under-represented in STEM. It is therefore important for the HEP to engage the vast community at PUI and CC which may serve as pipelines to improve diversity and under-representation in HEP. For such engagements to be productive, barriers to participation of PUI and CC faculties in HEP activities must be addressed. These barriers include heavy teaching loads, lack of guidance and research funds, lack of research infrastructure and equipment, and lack of administrative support and understanding of the regulations and requirements for successful participation in HEP—see Ref. [16] and the references therein. To address these barriers, we suggest the set of recommendations on institutional culture [3]:

The HEP community should encourage a global shift in perception, acknowledging that:

- Undergraduate research experiences are *key* to engaging a broader section of the student population.
- PUI or CC faculties have much to offer their collaborations, particularly in experiment-wide training and educational activities.

HEP experiments should offer coordinated communication from leadership to PUI administrators, extolling the features of high energy physics research alongside highlighted participation.

The HEP community should offer special sessions for PUI and CC faculty at national meetings to develop a deeper sense of community.

We also have suggestions for research funding [3]:

- Funding agencies should strengthen participation by PUIs in HEP by allocating funds for grants from these institutions, and **HEP experiments or laboratories** should fund grant-writing workshops.
- Funding agencies should allow course buyouts in proposals by PUI/CC faculty in order to boost productivity and establish continuity in PUI research programs.
- Funding agencies, HEP experiments, and laboratories should create or support paid summer programs for PUI faculty to work at National Labs or non-PUIs, as well as research opportunities for students not enrolled at major HEP institutions.
- Supervisors and HEP experiments should provide training to interested students and postdocs on US-specific research funding procedures.

Finally, We make the following suggestions for participation in HEP activities [3]:

- Non-PUI senior-level researchers should investigate how their groups could offer opportunities for short-term and long-term collaboration on their experiment to faculty and/or students at local PUIs.
- HEP experiments must reevaluate large fixed "entry fees" per institution, if they exist. Consider implementing "light" membership forms that are low cost but not time limited.
- US HEP experiment leaders should advocate with international experiment leadership for pathways to sustainable membership for PUIs, which are most common in the US. Postdocs should be aware of options for entering these pathways so they are not discouraged from applying to PUI faculty positions.
- HEP experiments must continue to improve options for remote participation in experiment meetings and service tasks, especially operational shift work.

3.3.3 Connections with other Frontiers and Topical Groups

Improvement in career pipeline and development requires improvement physics education as discussed in Section 3.5 to prepares a skilled workforce needed for HEP and career migrations industry and improve diversity, under-representation and inclusion in HEP as discussed in Section 3.4. HEP experimental physicists have developed expertise and transitioned into accelerator physics; this is essential to HEP operations and applications in industry, such as medical, materials, pharmaceutical, chemical and biological areas. Small scale experiments in neutrino, dark matter, nuclear and rare processes are sources of training for HEP physicists and transitions to industry. Technology transfers and applications and industry as discussed in Section 3.2, in addition to training in instrumentation and detector technologies, can enhance fruitful career transitions [3].

3.4 CEF03: Diversity, Equity and Inclusion

This topical group focused on issues and projects related to (1) Diversity, (2) Inclusion, (3) Equity and (4) Accessibility; all are essential not only to professional success in our field, but to developing a better society at large. The group gathered information concerning diversity, equity, inclusion and accessibility in high energy physics, instances of success and failure, and actions that have been taken to promote our tenets. Thirty-two letters of interest were tagged to this group; other inputs came from surveys, town hall meetings and discussions. Ultimately, twelve contributed papers were developed, as detailed in Ref. [4]. The contributed papers may be categorized as follow:

- Accessibility in High Energy Physics: Lessons from the Snowmass [17];
- Lifestyle and personal wellness in particle physics research [18];
- Climate of the Field: Snowmass 2021 [19];
- Why should the United States care about high energy physics in Africa and Latin America [20];
- Experiences of Marginalized Communities in HEP [21–25];
- In Search of Excellence and Equity in Physics [26];
- Strategies in Education, Outreach, and Inclusion to Enhance the US Workforce in Accelerator Science and Engineering [27].

3.4.1 Accessibility in High Energy Physics: Lessons from the Snowmass Process

Various barriers may impede on full participation in HEP activities; in Ref. [17], using the results of surveys, experiences and additional feedback from community members, and best-practice guidelines, the authors studied accessibility to engagements in HEP and offered recommendations for improvement. The authors discussed the resources and funding needed to implement the recommendations. Barriers to accessibility include lack of financial support, mental health issues, deaf/hard of hearing, visual disability/blind, caretaker responsibilities and virtual access. These barriers affect the community as a whole by impacting on the ability to collaborate with the members that face accessibility challenges. Survey respondents said that logistics for accessibility should not be the burden of the persons that need access; the availability of transcripts and auto-captioning were noted; however, these fail to transcribe correctly all ramifications of human expressions. Furthermore, resources available often require advance planning and funding and these are the core recommendations for organizing accessible physics events. More details on the studies done and recommendations can be found in Ref. [17].

3.4.2 Lifestyle and personal wellness in particle physics research activities

The demand of particle physics activities may result in an unhealthy imbalance between work and personal life. Unequal remunerations, living conditions and caretaker responsibilities and competitiveness for career progression, visibility, and grants, are among the causes for poor work-life balance. These career requirements lead to working after-hours, during weekends and holidays; teleworking may be impacted by living conditions

and may blur the boundaries of work and personal times. Such an imbalance may result in mental health issues, burnouts, poor job satisfaction, and poor performance [18]. Other triggers of work-life imbalance are the expected activities that do not translate into research outputs or are not compensated in career evaluations—these include work for community engagement as noted in Section 3.6, for DEI initiatives, mentorship, refereeing, reviews, hiring committees, etc. Furthermore, as noted Refs. [22–25], unwelcoming working environment that translates into discrimination, harassment, non-inclusion, code of conduct violations, etc., places undue burden on the victims and members of marginalized communities and lead to work-life imbalance. In Ref. [18], the authors propose recommendations or actions to improve work-life balance.

3.4.3 Climate of the Field: Snowmass 2021

The state of existing policies and their effectiveness to create an inclusive, equitable and safe environment for HEP engagements are discussed in Ref. [19]—"climate of the field". In many scientific engagements, code of conduct guidelines are in place to define respectful interactions. Mechanisms to address violations are also defined. Yes, implementation of these guidelines and how violations are reported and addressed, are affected by the "climate of the field". An example is how a violation is handled when it occurs in a collaboration and the concerned parties (perpetrator and victim) have different institutional affiliations. Often, group dynamics and power dynamics lead to an inability to adhere to code of conduct guidelines and address violations; this creates an unwelcoming environment and alienates victims and marginalized folks; as noted in Ref. [18], it also impacts on work-life balance. The contributed paper of Ref. [19] provides recommendations for several top-down approaches that should be implemented by the community as well as recommendations for funding agencies to support these approaches.

3.4.4 Why should the United States care about high energy physics in Africa and Latin America?

Contributions of developing countries to high energy physics activities are hampered by limited resources and national priorities. Title VI of the 1965 Higher Education Act [28], designed "to support US national interests and maintain global competitive edge in the international arena", is a compelling reason for the United States to support HEP in developing countries. Mechanisms and recommendations to improve HEP engagements with Africa and Latin are articulated in Ref. [20] where it is argued that such sustained engagements will help international development, improve diversity and increase the participation of developing countries in HEP.

3.4.5 Experiences of Marginalized Communities in HEP

Power dynamics, informal socialization, policing and gate keeping in HEP create an environment and culture that alienate under-represented physicists and negatively affect their participation. Often, privileged folks lack awareness and attention or focus on perception rather than reality; therefore, they hang on to claims of objectivity in physics which only serve to maintain the culture of under-representation and non-inclusion, to deny the negative experiences of marginalized physicists, and to expect them to shrug off these bad experiences, despite the harm caused, in order to be taken seriously as physicists. The key to improve

the experiences of BIPOC physicists consists of addressing the complexity and impact of power dynamics, policing and gate keeping [23, 24], and implementing actions individuals and organizations can take to lower barriers for early career BIPOC physicists [25].

Despite all the efforts and investment to improve DEI in HEP, these issues remain as demonstrated in Refs. [21–25]. We offer concrete suggestions towards improving DEI; these suggestions include effective approaches to reach members of marginalized communities through engagements as discussed further in Section 3.6 and Ref. [21].

3.4.6 In Search of Excellence and Equity in Physics

The claims of objectivity in physics lead to meritocracy, i.e. the idea that "scientific work is judged on its merits and that opportunities in physics are equitably available to all aspirants". However, as demonstrated in Ref. [26], there is far more under-representation than could be expected from meritocracy. This further challenges the claims of objectivity in physics, along similar lines as Refs. [21–25]. To address this, changes in community practices are needed; we should challenge or verify organizational claims of equitable access. Focused efforts, continuous measurements and frequent corrections are required to achieve fair procedures, eliminate barriers and improve under-representation [26]. The physics community should seek best practices on how to combine equity and excellence; the private sector has made some progress to match best practices to company values, thus mitigating damages resulting from public exposure of misconduct. The need to enforce codes of conduct and to address violations, mentioned in Ref. [19], are also echoed in Ref. [26]. The American Physical Society has made efforts towards an equitable, diverse and inclusive field; however, community participation is required to improve excellence and equity. Meritocracy, instead of cronyism, is important to identify leaders. In Ref. [26], the authors go further to suggest recommendations towards an ethical hiring process for excellent leaders that will uphold the values of equity.

3.4.7 Strategies in Education, Outreach, and Inclusion to Enhance the US Workforce in Accelerator Science and Engineering

Accelerators, large or small, play important roles in fundamental research and applications; they are essential to discovery science and high technology, thus can help to train a strong technical workforce needed for particle physics research. In Ref. [27], the educational and outreach opportunities available in accelerator science and engineering are reviewed, with the objectives to attract talents and develop capacity for future R&D; in this process, the need to improve diversity, equity and inclusion is noted—the participation of women in the US Particle Accelerator School (USPAS) has increased; however, under-representation of women and historically marginalized groups still persists. Recommendations are proposed to improve diversity, equity and inclusion in accelerator science and engineering [27].

3.4.8 Suggestions to Improve Diversity, Equity and Inclusion in HEP

From the aforementioned work in Section 3.4, we have prepared suggestions and resources that are tailored to particle physics, cosmology, and astrophysics, to further promote diversity and encourage equity, inclusion and accessibility at all levels of scientific discourse, engagements and managements.

3.4.8.1 Suggestions for Funding Agencies

HEP communities should improve use of robust strategic planning procedures, including a full re-envisioning of science workplace norms and culture:

- Prioritize community-related issues at the funding level, e.g. inclusion of community-related topics into safety parts of collaboration "Operational Readiness Reviews," "Conceptual Design Reviews," or similar documentation submitted to funding agencies. Funding agencies should provide clear and enforceable requirements for the advancement of DEI issues in grants, programs, and evaluations [19].
- Funding agencies should provide formal recommendations for institutions, research groups and collaborations for handling violations of their codes of conduct. This should include advice on handling community threats, removal of collaboration affiliates, leadership rights and responsibilities, and protections against legal liability for leadership that is responsible for that enforcement. This should also include advice on reporting to the funding agency itself; if there is no mechanism for reporting misconduct to a funding agency, that mechanism should be developed [19].
- Funding and structural aid should be made available to develop "Collaboration services" offices at host laboratories. Such offices should provide HEP collaborations and other physics communities of practice with the following: a) advice on legal and policy topics, b) training in project management and ombudsperson training, c) logistical tools including facilitation of victim-centered investigation and mediation, d) resources and funding for local meeting accommodations, and other topics as described here in Section 3.4.8 [17, 19, 23, 25, 26].
- Funding agencies should use their leverage to promote community-focused policies at funded institutions. Funding agencies should require institutions that receive funding to implement policies on vacation time, parental & family leave (for all genders), and health leave for all levels. Funding agencies should require institutions to prohibit confidentiality in settlements for egregious behavior (e.g. harassment); this promotes accountability and prevents known perpetrators from continuing to harm their communities [18, 19].
- Funding agencies should establish a dedicated Office of Diversity, Equity, and Inclusion to work with Program Officers to strategize and prioritize funding decisions and develop equitable practices for the review processes [21].

HEP communities must implement new modes of community organizing and decision-making that promote agency and leadership from all stakeholders within the scientific community:

- Funding agencies should facilitate Climate Community Studies. Studies should not be the responsibilities of individual communities. These studies should be informed by expertise in social and organizational dynamics [19].
- Grant calls and assessments should include clear definitions of the tasks expected of PIs, including DEI related tasks, and provide grant funding for each. Alternatively, agencies could provide specific grants and awards for EDI and mentorship work. Agencies should ensure that they pay those on their grant review panels for their time [18].
- Funding agencies should collect, analyze, and publish demographic information on grant proposals and funded grants. PI and funded *and unfunded* researcher demographic information on grant proposals should be collected and used to track the effectiveness of these measures and are necessary to inform any additional policy changes needed to advance DEI policies and structures [18, 25].

- Pay for fellowship- / grant-funded student and postdoctoral researcher positions must increase. Pay should include cost-of-living adjustments, health / wellness / leave benefits, and relocation expenses [18].
- The US HEP community should maintain the current engagements and increase investments in Africa and Latin America to improve the reach of HEP in these regions. Funding agencies and international collaborations should acknowledge the disparity in economic capabilities of countries in Africa and Latin America compared to what is available in the United States. Funding agencies should support the development of HEP in these countries, should support and lead initiatives for more equitable contributions (e.g. membership and operations fees for participation in large collaboration, conference fee waivers and travel support to US-based meetings, etc.) [20].

HEP communities should develop partnership with scholars, professionals, and other experts in several disciplines, including but not limited to anti-racism, critical race theory, and social science:

- Funding should be made available to both engage with and compensate experts in DEI, anti-racism, critical race theory, and social science. This can take the form of independent grants, but more effective would be the inclusion of climate-related topics into safety components of collaboration "Operational Readiness Reviews," "Conceptual Design Reviews," or similar documentation submitted to funding agencies [19].
- Community studies should be run by and receive advice from experts in sociology and organizational psychology. The tools used to evaluate the climate of HEP need to be adequate, effective, and informative. These studies and accompanying expertise should be funded at the federal and institutional levels. They should include evaluation of leadership selection, development of junior scientists and their trajectories, and the existence of detrimental power dynamics that specifically affect underrepresented groups. Undesirable systems should be addressed with direct intervention [19, 23, 25].
- Grant calls and assessments should include the advice of professionals in DEI and education. Such experts should review the entire process, including portfolios in their entirety, but with specific attention to mentorship and DEI plans. Experts should be paid for their time [18].

3.4.8.2 Suggestions for HEP Communities

HEP communities should develop or improve robust strategic planning procedures, including a full re-envisioning of science workplace norms and culture:

- HEP communities should support and take advantage of existing support structures and informational networks. Tools exist to support efforts to improve diversity and inclusion, as well as to address injustices in our communities. These include the American Association for the Advancement of Science (AAAS) Diversity and the Law program [29] which hosts resources to enable promotion of legal and policy goals related to DEI. Knowledge like that collected by the American Institute of Physics' National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) Project [30, 31] and the AAAS's STEMM Equity Achievement (SEA) Change [32] should also be promoted [23].
- Institutions and HEP communities must develop reporting mechanisms and sanctions for egregious behavior. These institutions and communities should transparently describe those mechanisms in full for the benefit of all affiliates. Communities must be prepared to exercise those mechanisms. Future HEP community codes of conduct should align with, and current codes of conduct should be

reviewed upon new recommendations from funding agencies regarding enforcement and disciplinary measures [19].

- The community should prioritize the implementation of best practices networks across institutions and communities of physics practice. This may be facilitated through Collaboration Services Offices, but may also include the facilitation of networks between DEI groups at similar collaborations [19].
- All community affiliates should reject harmful rhetoric and behavior related to work-life balance. This includes "ideas around 'lone geniuses', the need for unhealthy work schedules, and the idea that sacrifice of personal wellness demonstrates your commitment to science" [18]. Senior scientists are responsible to ensure that they are managing their time and the time of those in their group properly to respect work-life balance (including reducing meetings outside of working hours, or rotating meetings to accommodate varying time zones) [18].
- Departments and institutions should have clear definitions of job responsibilities and ensure that they are funding all functions of the job. This includes any DEI work. Assessments should weight work in these areas equally and individuals should be awarded and/or recognized when they excel. Evaluation for employment should be based on carefully developed, public rubrics that include DEI, outreach, and service. Such rubrics should be created with considerable care and research-driven (e.g. if any of the criteria are biased in a way that would limit access or promotion of people who identify with an underrepresented group) [18, 19, 25].
- Departments and institutions should reject the use of standardized exams in favor of holistic rubrics for admission. Evaluation for admission should reject the use of standardized exams and instead should be based on carefully developed, public rubrics, that are tailored to the department. Such rubrics should be created with considerable care and be research-driven (e.g. if any of the criteria are biased in a way that would limit access or promotion of people who identify with an underrepresented group) [18,19,25].
- Graduate students and postdoctoral researchers should be paid at the level of their respective skill levels. This includes benefits like relocation services, health coverage (including families), retirement savings, subsidized family housing, and are not taxed for fellowship money they do not receive as pay. These benefits must apply while students and their families are abroad on behalf of HEP activities [18].
- Institutions should have accessible, clear, robust, and flexible policies for parental / family leave (for all genders) and vacation time. These should be guaranteed at all levels. Junior scientists should be made aware of and encouraged to take advantage of institutional policies and resources on diversity, health, leave, vacation, and wellness [18].

HEP communities must implement new modes of community organizing and decision-making that promote agency and leadership from all stakeholders within the scientific community:

- Reviews of community climate should include an evaluation of how leadership is selected within HEP collaborations, as well as the valuation of sub-community contributions. This should include a expert-advised review of the assignment of high-impact analyses & theses topics, convenership of working groups, and public-facing roles representing the collaboration such as spokespersons or analysis announcement seminars. Power dynamics within communities should also be evaluated, and should consider the impact that senior scientists can have especially on junior scientists of color. It should also include reviews of the participation of "non-scientists" in community engagement and authorship, community perceptions of operations and service work, the development of onboarding and early-career networks, and implementation of policies toward equity in information sharing and software [19, 23, 25, 26].

- Collaborations should train members in standards in the field and offer mentorship programs to ensure that postdocs and students (especially from underrepresented groups) have additional support and resources. Mentorship programs should be research-driven and should make access to information as ubiquitous as possible. Mentors should help novices navigate the complicated landscape of the community, and care should be taken to address the "untold rules", like non-academic career trajectories. Information sharing, especially about collaboration policies, procedures, and code-bases, should be evaluated from an equity lens [18, 19, 25].

- Conferences should offer financial assistance to individuals with hardships. Conferences should offer limited travel grants through an application procedure overseen by an ethics group associated with the conference. To promote the engagement of under-resourced and early-career scientists, conferences should also strongly consider developing an application for sliding-scale / waiver for conference registration fees. Conferences should accommodate care-giving responsibilities by providing childcare onsite, or by supporting the travel of an accompanying person. In both situations, extra funding should be budgeted by the conference to fully or partially cover those costs [17].

- The organizers of all HEP activities should ensure that people with accessibility barriers are truly accommodated, with guaranteed, low-friction, dignified access to all aspects of the experience. All conferences, collaborations, universities, and labs should be made accessible to people with disabilities. For example, conferences (including virtual meetings) should be announced with enough time to arrange accommodations for any individual needs, and organizers should plan to secure funding and book services far enough ahead of time. Accommodations should include both steno-captioning and ASL interpretation, which should be fully funded as part of the conference budget. Conferences should also be accessible to the blind / low-vision community, which may include screen-reader-accessible tools and "color-blind-friendly" plots. Other accommodations include: seating or accessible access to amenities like check-in and meals; locating the conference in ADA-compliant buildings with no obstructions to seating, entrances / exits, or accessible pathways; quiet spaces; and designated contacts for troubleshooting accessibility. An extensive list of recommendations can be found in [17].

- US universities and research labs should encourage and support the participation of their personnel, faculties and research staffs in HEP education and research efforts of African and Latin American countries. US institutes need to partner with Latin America and Africa in establishing bridge programs and supporting community members from Africa and Latin American to come to United States laboratories and universities for research experience programs. Collaborations and conferences should seriously consider decreasing or waiving membership and operations fees for participation and should provide financial assistance for travel to the United States [20].

HEP communities must engage in partnership with scholars, professionals, and other experts in several disciplines, including but not limited to anti-racism, critical race theory, and social science:

- Experts should be adequately integrated into HEP communities. This is motivated by the need to apply their expertise effectively, and should include collaboration communities. This may take the form of an official collaboration role like a non-voting member of a collaboration council [19].

- Identification of leaders within HEP communities should be research-driven. HEP organizations and institutions require leaders who will promote policies and practices that support underrepresented and historically marginalized groups instead of favoring "politics and convenience". Best practices have been developed by industrial & organizational psychologists and are under studies at NSF (e.g. [33]). Details on necessary search practices can be found in [26].

3.4.8.3 Suggestions for Future Snowmass Activities

- Community Engagement topics should be better integrated into other frontiers. This work is the responsibility of *all* HEP community members, and should not be relegated entirely to an independent, volunteer-driven frontier.
- Funding for Snowmass activities should include critical infrastructure for accessibility. This includes live captioning for all public events, and infrastructure for hybrid meetings to support those who cannot travel to attend workshops.

3.5 CEF04: Physics Education

CEF04, the Physics Education (PE) topical group, examined the role that physics education at all levels plays in advancing the field of HEP. Two goals were identified as critical for the long-term health of the field: 1) attracting students across all demographics to the study of physics, and 2) provide them the education, training, and skills they will need to pursue any career in STEM or related fields. The CEF04 Topical Group Report puts forth recommendations intended to achieve these goals by strengthening ties between researchers and teachers, the academy and the private sector, and domestic and international students [5].

The PE group framed its studies according to the pyramidal scheme displayed in Figure 3-2. This diagram rises from the relatively large number of K-12 science students at the base up to the small apex of faculty-level physicists. The work was organized into four groups, each of which produced a contributed paper presenting detailed examinations of physics education challenges and opportunities at each level. The working group contributed papers are:

- Opportunities for Particle Physics Engagement in K-12 Schools and Undergraduate Education [34];
- Transforming US Particle Physics Education: A Snowmass 2021 Study [35];
- Broadening the Scope of Education, Career and Open Science in HEP [36];
- The Necessity of International Particle Physics Opportunities for American Education [37];

3.5.1 Particle Physics Engagement Opportunities in K-12 Education

The first working group found that partnerships between academia and K-12 teachers and students are effective in nurturing early student interest in math and science. It is important to provide a broad exposure to the different STEM fields at all levels in order to develop properly their scientific literacy. The key recommendation for forming these partnerships is:

- **At the local level, form collaborative communities ("fora") of academics of all backgrounds (physicists, engineers, technicians and K-12 teachers). (CEF04 Recommendation 1)**

  To create these fora, a minimal amount of support for coordination and logistics will need to be available. Then to function well and avoid isolation, they need to be supported by a nationally, or even internationally, organized online repository for sharing resources. To be sustainable, it

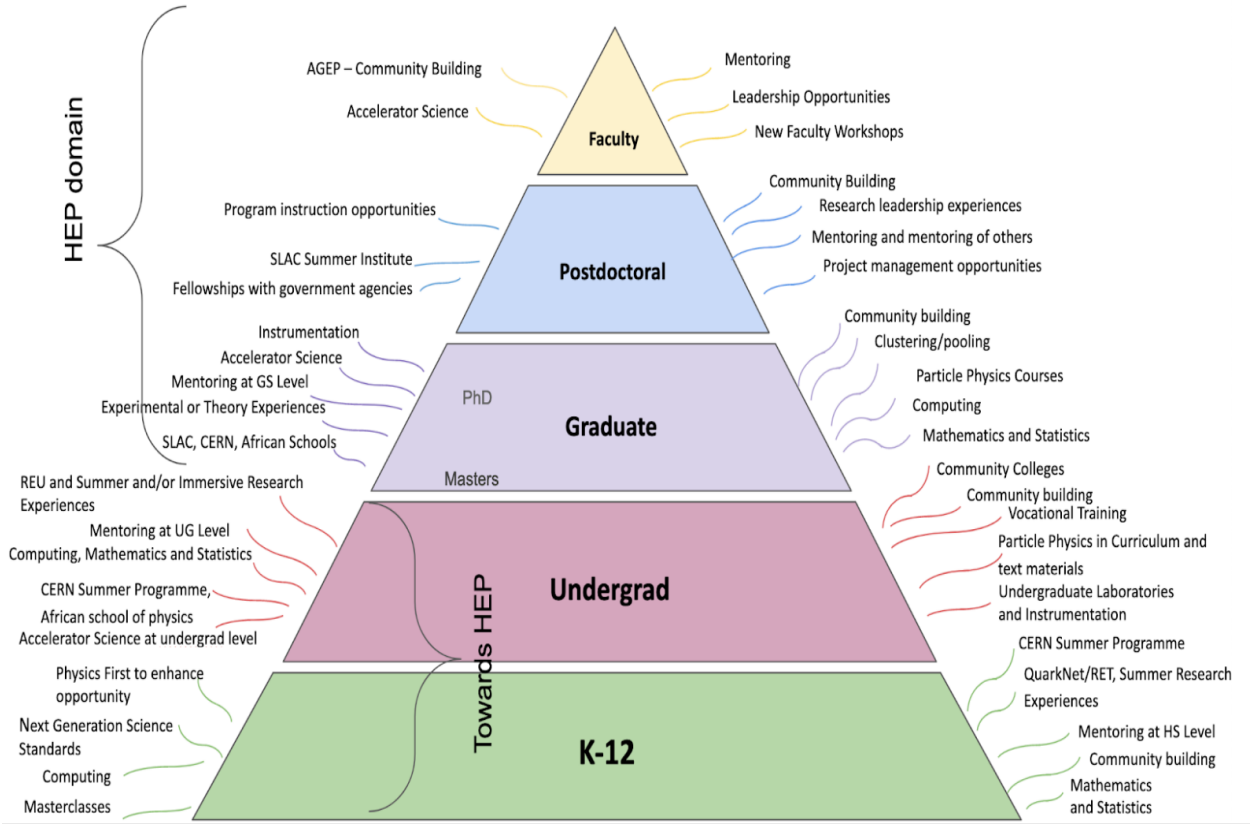

Figure 3-2. *A Schematic Representation of Particle Physics Education*

will be important to have a steady source for continued support, which could come from colleges, universities or institutes, but might also come from or be supplemented by outreach support in the form of research grants. Another important ingredient for sustainability is that the efforts of the fora participants are appropriately and regularly recognized. (CEF04 Recommendations 2,3)

3.5.2 Educational Opportunities at the Undergraduate, Graduate and Postdoctoral Levels

Education and training specific to particle physics generally begins with college undergraduates, and continues during the graduate student and postdoctoral researcher stages, and usually takes place at universities and laboratories. An online survey of the US HEP community was conducted to gain insight on students' experiences during this phase. On one hand, respondents indicated that this is the point at which students are expected to gain the skills necessary to launch a career in HEP or related fields. However, they also expressed that the training they received through formal education did not match the skills needed to succeed in physics. In contrast, many of the most important skills they routinely use in their research were learned "on-the-job." To better prepare students for physics careers, updates to formal university training is recommended [34].

- **University degree programs should normalize training for particle physics and a broad range of STEM careers through inclusion of appropriate formal courses and career mentoring. (CEF04 Recommendations 4,5)**

  There is a need for graduate programs in particle physics to provide formal courses with strong grounding in particle physics and mathematics, but also computation, statistics and instrumentation. This course instruction will benefit student careers in physics, industry or education, because the students will not be forced to resort prematurely to self-teaching or peer learning alone. Universities should provide undergraduate students with a more complete picture of what particle physics researchers do. By presenting a realistic view of common career paths post baccalaureate and postgraduate school, students will be better prepared to pursue options including theoretical and experimental positions as well as non-academic careers.

  The survey data was limited due to minimal undergraduate participation. This low response was due in part to a lack of connection information for the undergraduate demographic. Support from professional societies and Physics Departments could provide opportunities to strengthen connections and networking for undergraduate students with HEP community activities, and to develop a future survey focused on undergraduate participation. (CEF04 Recommendation 6)

The physics community and HEP in particular, tends to be fairly "PhD driven." It is worth investigating whether a Masters degree program in particle physics could fill an important career path need in our field. Masters programs often have the opportunity for more cross-disciplinary work in adjacent fields such as engineering or computer science. Professional level Masters degrees could attract students working in private companies pursuing career advancement through continuing education, and build stronger bi-directional ties between HEP and the industry sector. PhD programs in physics often present strong structural barriers to many students from traditionally underrepresented groups, while a Masters degree could offer an intermediate and more achievable goal, and perhaps lead to greater diversity in HEP.

- **Universities, especially non-research universities, should consider setting up Masters Degree programs in particle physics and related areas, such as hardware and software technology for Big Science experiments. (CEF04 Recommendation 7)**

3.5.3 Collaborative Opportunities Across Academia

An important challenge for HEP is the need to broaden and diversify the pool of talent and expertise drawn to the field. A crucial part of the solution to this problem is to build more collaborations between groups at the R1 research institutions that traditionally represent the vast majority of the HEP community, with R2 institutions, Predominantly Undergraduate Institutions (PUI), and Community Colleges (CC).

- **Expand the benefits of faculty collaboration and research opportunities across the broad spectrum of academia and give equivalent opportunities for all in technical and scientific leadership on projects, with appropriate recognition for contributions. (CEF04 Recommendation 8)**

  A study of new models of collaboration or cooperation that would allow R2/PUI/CC faculty and their students to participate effectively in experiment collaborations could help address the

challenges of teaching loads, student training and funding availability that directly impact our non-R1 institution colleagues ability to fully contribute to projects. Making data and analysis platforms broadly accessible will benefit student access and participation. The HEP community should embrace the value of Open Science by defining the scope of making our data and resources publicly available, and the hardware, software and person-power costs associated with such implementation. (CEF04 Recommendations 9,10)

Fields such as instrumentation, computation, and machine learning have become critical components of the HEP enterprise. However, career paths at the intersection of particle physics and these specialized fields are not very clear or easy to navigate, nor universally recognized as "physics" work. Improving this situation would simultaneously address pipeline and retention issues within HEP, and equipping colleagues for careers outside the field.

- **Qualification for HEP faculty jobs should not be based solely on physics analysis but rather expanded to include computing, software and/or hardware contributions. (CEF04 Recommendation 11)**

3.5.4 International Opportunities for Particle Physics Education

High Energy Physics is conducted through global international collaborations. These diverse partnerships enrich the intellectual environment of our field. As such, training in international collaboration throughout the educational process will facilitate more productive integration of talent and resources in future projects:

- **U.S. based pre-university particle physics collaborations should expand collaboration with international partners. (CEF04 Recommendation 12)**

  Collaborations such as QuarkNet and other outreach programs, such as the International Particle Physics Outreach Group (IPPOG), the CERN Beamline for Schools (BL4S) and Teacher summer school programs in Europe, should partners with counterparts in the developing world, such as the African School of Fundamental Physics and Applications. Participation in the Global Cosmics portal should be enhanced by developing low-cost cosmic ray detectors for educational use.

- **Student exchange programs should be fostered and supported. (CEF04 Recommendation 13)**

  These programs include the NSF Research Experience for Undergraduates (REU), which funds participation of U.S. students in the CERN Summer Student program, and the DoE-INFN summer student exchange program between the U.S. and Italy. Where possible these should be extended, in particular with student exchange programs and summer schools in developing countries, such as the African School of Fundamental Physics and Applications.

3.6 CEF05: Public Education and Outreach

The CEF05 working group focused on enabling members of the physics community to effectively communicate about scientific research through public engagement.

Thirteen LOIs were tagged to the Public Education and Outreach topical group. Some of them were consolidated and developed into contributed papers in Section 3.4 about diversity, equity and inclusion [21,27] and Section 3.5 about physics education [34,36,37]. Other LOIs were condensed into two contributed paper topics, namely:

1. The need for structural changes to create impactful public engagement in US particle physics" [38];
2. "Particle Physics Outreach at Non-traditional Venues" [39].

CEF05 collected input through a variety of methods. In addition to reviewing the LOIs, the group invited experts to their regular meetings for discussion and conducted a survey of the physics community.

The majority of the survey's 358 respondents said they had participated in outreach activities. They mentioned that they were discouraged from participating in public engagement because they did not have enough time and because it generally did not benefit their careers. They were motivated to participate, though, because they wanted to reach underserved groups, to show openness or explain the scientific method to the public, to share their enthusiasm, and to inspire the next generation of physicists. In their engagement, they used storytelling and shared their own reasons for pursuing physics. Respondents said the best way to get involved in public engagement was to start small and gain experience by finding and plugging into established engagement programs. Details on the group activities are compiled in the topical group report [6].

The group identified several structural and cultural barriers to participation in public engagement. To remove those barriers and encourage physicists to engage the public, the group made specific recommendations aimed at research groups, experimental collaborations, conferences, universities and colleges, national laboratories, OSTP, Congress, DOE, NSF, private foundations, AAAS, APS, and DPF [38].

In general, the group recommends:

- Providing or financially supporting training in effective public engagement
- Supporting the creation of public engagement programs that scientists can participate in
- Codifying the importance of public engagement in official documents such as:
  - Laboratory contracts
  - Faculty handbooks
  - Professional society strategic plans
  - Experimental collaboration constitutions
  - Merit criteria used by institutions that fund research
- Considering public engagement along with activities such as service and teaching in:
  - Hiring
  - Tenure
  - Promotion
  - Other reviews
- Funding public engagement work as part of grant proposals
- Incorporating public engagement into conferences and meetings in the form of

  - Plenary talks
  - Parallel sessions
  - Public lectures
  - Training opportunities for conference participants
  - Public engagement opportunities for conference participants
- Recognizing and rewarding scientists who contribute to public engagement efforts

The group also recommends individual scientists encourage others, including peers, mentees and students, by participating in public engagement and discussing its importance.

For the next Snowmass process, CEF05 recommends a shift in focus from "public outreach" to "public engagement": two-way interactions that ensure mutual learning, which goes beyond the acquisition or transmission of knowledge and includes the understanding of perspectives, worldviews and socioeconomic backgrounds. Some innovative ideas on public engagement are discussed in Ref. [39], and details are provided in the topical group report [6].

The group recommends updating the topical group name from "Public Education and Outreach" to simply "Public Engagement" to reflect this shift in priorities, and also to clear up confusion between the goals of CEF05 and CEF04, the topical group focused on education.

Public engagement can help recruit and retain scientists from diverse backgrounds, thus improving diversity as discussed in Section 3.4. Therefore, learning how to reach members of marginalized communities via public engagement is essential. Public engagement conducted without proper preparation can be counter-productive and harmful [40]. Working toward addressing the needs of the intended community must be the objective, achievable through building relations and inclusion [21]. A detailed checklist of questions for institutions to address when preparing to engage marginalized communities is mentioned in Section 3.4 and recalled here.

Consider the audience:

- Who specifically are we hoping to reach with this event? Why are we hoping to reach these communities?
- How can we plan this event to make it maximally beneficial to these communities? What elements of this plan can we continue to use in other events?
- What are the best ways to communicate about this event with members of these communities? Can we continue going to those same channels to communicate about other events?
- Have we created a process by which we take time to evaluate the success of the event after it concludes?
- What metrics (both qualitative and quantitative) will we use? Which of these metrics will we continue to use in evaluating other events?

Identify and remove barriers:

- Are there logistical barriers (e.g. time of day, day of the week, public transportation access, affordability, safety concerns, financial barriers) to our events that make them inaccessible to these communities? What will we do to address these barriers?

- Have we allowed adequate lead time and budget to make this event accessible to all members of these communities, including those with disabilities? Have we identified partnership or staffing needs required to make the event accessible?

Value partnerships:

- What members of these communities will make good partners in this event? Have we made sure they're involved in planning the event? Have we secured an adequate budget to support fair compensation for our partners as co-creators of the event, prior to requesting their labor?
- Do any members of these communities work for our institution? If they do, do they work in roles with decision-making power (e.g. managerial positions), or do they work primarily in service roles? If members of these communities do not work at our institution, or work only in lower-level positions, is our institution making any effort to change this?
- Are members of these communities who work for our institution participating in this event? If so, are they receiving the support they need to take on this effort and fulfill their other job duties? Do they have decision-making power over the planning and execution of the event? Are they being fairly compensated and recognized for their efforts?

Build lasting relationships:

- Is this event a part of a larger effort to build relationships with members of these communities? If so, what is the long-term plan? Who will be responsible for enacting it?
- Are there ways in which our institution is causing harm to members of these communities? If so, how is our organization working to change this?
- How are representatives of our institution involved in these communities outside of this event? Are there ways our institution can work with members of these communities on their priorities, even ones that do not directly benefit our institution?

CEF05 recommends finding ways to implement the structural changes needed for improved public engagement. The group further recommends that the physics community build lasting relationships with marginalized communities through public engagement; this will contribute to improve diversity in HEP as discussed in Section 3.4. Finally, CEF05 recommends that the American Physical Society's Division of Particles and Fields monitor progress toward these goals leading up to the next Snowmass process.

3.7 CEF06: Public Policy and Government Engagement

The topical group CEF06: Public Policy and Government Engagement (PPGE) was tasked with conducting a review of all current interactions between the HEP community and government offices and individuals. This enterprise includes identification of consensus positions on policies with direct impact on our field, development of unified messages from HEP to those determining and implementing policy, and creation and deployment of tools and resources to effectively communicate those messages in a manner resulting in positive policy outcomes. Those working in CEF06 identified areas of HEP government engagement that are missing or in need of improvement, and developed recommendations to address these opportunities. Three contributed papers produced by CEF06 document this work:

- Congressional Advocacy for HEP Funding [41];
- Congressional Advocacy for Areas Beyond HEP Funding [42];
- Non-congressional Government Engagement [43].

and details of the analysis, synthesis, and recommendations based on those papers is presented in Ref. [7].

3.7.1 HEP Funding and Advocacy Organization

Over the past few decades, HEP communication with government has largely focused on advocacy for strong federal budget support for HEP, which comes almost exclusively through the Department of Energy (DOE) Office of Science (OS) and the National Science Foundation (NSF). Funding of federal government programs is an extremely complex cyclical process; however there are three basic steps that provide target points for our advocacy. The first is the creation of the annual President's Budget Request (PBR), which is formulated by the Office of Management and Budget (OMB), with advice from the Office of Science and Technology Policy (OSTP), which works closely with DOE and NSF. The second step is for Congress to pass a budget, which sets topline numbers for funding each major area of government spending. Although the Budget Committees create the budget, it is informed and guided by individual authorization bills, which specify what Congress may spend money on, and these bills come out of authorization committees. Getting specific language supporting HEP programs into authorization bills greatly increases the likelihood of positive funding outcomes. The third major step is appropriations. Appropriations Committees make the decisions on the actual yearly allocation of funds to all government agencies and programs within the constraints of the Congressional budget topline numbers.

The DOE OS and NSF receive HEP program planning advice from a federal advisory committee, the High Energy Physics Advisory Panel (HEPAP). HEPAP has a subpanel known as the Particle Physics Project Prioritization Panel (P5), which produces reports detailing long-range strategic plans for US HEP that are largely based on studies resulting from the Snowmass community planning process. The most recent P5 report from 2014 has served as the core of our field's message and advocacy to government for nearly a decade. The effectiveness of our messaging and advocacy over this time is indicated by the fact that DOE funding of HEP has grown by 36%, or roughly $300M since 2015. This advocacy is carried out jointly by the Fermilab Users Executive Committee (UEC), US-LHC Users Association (USLUA), and SLAC Users Organization (SLUO) with help from the American Physical Society Division of Particles and Fields (APS DPF). However, this group does not have the mandate nor resources to address any aspects of engagement with the government beyond federal funding advocacy (and not enough even to sustain fully that activity). Some new structure must be put in place to broaden HEP's engagement with government to effectively work for policies to strengthen our field.

- **Representatives of APS DPF, HEPAP, and the user groups, as appropriate, should have dedicated discussions to determine what actions can be taken to advance the recommendations outlined in this report [7]. (CEF06 Recommendation 1)**

3.7.2 Message Unity Around P5

Advocacy for the 2014 P5 plan has been very successful, leading to a current DOE budget for HEP in excess of $1B. Critical elements of that success are that P5 represented a single comprehensive plan for the entire US

HEP program that had community-wide buy-in, and this led to one unified message that our field delivered to Congress and the Executive Branch. Prior to the 2014 P5, our messaging was fragmented, with people inside and outside the HEP community bringing their own takes on the HEP program to policymakers that were inconsistent with our community-organized advocacy. HEPAP and the 2023 P5 have to lead the effort to build a consensus message around the new P5 plan. This has to include both educating the community and the government about the new plan, and for the updates and changes to the plan that will inevitably occur.

- **HEPAP should build community unity around the 2023 P5 plan and develop a clear messaging strategy spanning the next 10 years. (CEF06 Recommendation 2)**

  Building consensus will require short-term steps related to the drafting and roll-out of the P5 plan. There must be ample opportunity (outside of HEPAP meetings) for internal presentation and community feedback on the draft plan before its release. Once the plan has been finalized, P5 will need to launch an "education campaign" to communicate details about the plan to HEP community members and other stakeholders such as the funding agencies and policy makers. (CEF06 Recommendations 2.1-2.2)

  Long-term actions to maintain message unity consist largely of ensuring good communication. Each year since 2014, the P5 chair has produced a one-page status report that has proved invaluable for Congressional advocacy among other things. A formal commitment should be made to continue producing those reports. More detailed regular reports and feedback opportunities for the community on P5 plan implementation progress, modifications, and impacts will be crucial for keeping the field united behind the plan. (CEF06 Recommendations 2.3-2.6)

  Because P5, by definition, is focused exclusively on projects, it has never before directly addressed issues of community engagement, and it is not structurally set up to do so. However, community engagement issues have become extremely important to the healthy functioning of our field, including our projects. P5 will need to explicitly consider relevant community engagement concerns in its work in order to keep the field unified. (CEF06 Recommendation 2.7)

3.7.3 Congressional Advocacy for HEP funding

The community's advocacy for federal funding support of HEP largely consists of the annual trip to Washington, DC, during which a group of our colleagues meet with as many Congressional offices as possible, as well as with OMB, OSTP, DOE, and NSF. The 'DC Trip' is organized by UEC, USLUA, and SLUO each spring to fall between the release of the PBR and the markup of appropriations bills. These users organizations are composed of elected representatives of our community, and the roster of trip attendees is intentionally selected to broadly represent the entire field. However, the users groups are not fully representative of the field, so the formation of a new broader "HEP Congressional advocacy" group should be considered. The DC Trip has grown dramatically over the past two decades. Around 2004, roughly 25 attendees visited about 150 offices. With increased funding support, by 2019 almost 70 attendees visited all 541 Congress members' offices as well as 8 subcommittee staff and the Executive Branch offices.

- **Representatives of UEC, SLUO, USLUA, and APS DPF should facilitate discussions to consider the formation of a more formal "HEP Congressional advocacy" group to assume responsibility for organizing the annual advocacy trip to Washington, D.C. (CEF06 Recommendation 3)**

- **The HEP Congressional advocacy group should continue to support, and should aim to grow, the annual HEP community-driven advocacy activities. (CEF06 Recommendation 4)**

  The DC Trip requires a huge organizational effort that has been made possible by the development of a number of tools and resources. Foremost among these is the Washington-HEP Integrated Planning System (WHIPS), which is a framework to automate most of the planning, execution, and documentation logistics. WHIPS compiles information on Congressional districts, offices, and committees, tracks all past and future meetings, and uses data on trip attendees' personal, work, and family connections to districts to assign attendees to specific Congressional offices. It is the key tool that has enabled HEP advocacy visits to achieve complete coverage of Congress. There is also a twiki repository of trip information and an HEP funding and grant database, both of which could be expanded to include more granular district-level information. These resources have all been developed and maintained by the volunteer effort of a handful of early career colleagues without permanent positions, some who are no longer within the field. A more permanent plan for further maintenance, development and sustainability of these and new tools must be implemented to ensure their continued availability. (CEF06 Recommendations 4.1-4.2)

  One question colleagues often ask about HEP advocacy is "How do we know it is effective?" What are the diagnostics and metrics that we use to measure the benefit of the advocacy efforts? WHIPS can track information such as Congress members' voting records on specific legislation and signatures on Dear Colleague letters, and even match those members' activities to the HEP trip attendees who visited those offices. However, long-term collection and analysis of the data will require resources beyond current trip planning and participation. (CEF06 Recommendation 4.3)

  There are many professionally-produced communication materials created for the DC Trip. These documents convey our advocacy messages to government offices, and many also serve to share different aspects and benefits of HEP to other audiences. They have been developed by the user organizations in concert with the Fermilab Office of Communication, DOE, and the P5 chair, but there is no guarantee that those groups and individuals will be able to continue providing that support. Investments in maintaining those production partnerships should continue. (CEF06 Recommendation 5)

  Training materials have also been created to prepare community members for their participation in the DC Trip, and this training has been crucial for enhancing the professionalism and effectiveness of our advocacy. These materials must be regularly updated and deployed. In addition, making them available to the wider HEP community will enable expansion of our advocacy and help ensure unified messaging. Further inreach efforts to inform the field about our advocacy through more frequent talks and annual reports would also help achieve these goals. (CEF06 Recommendations 4.4-4.5)

  Some specific aspects of the DC Trip require specialized knowledge and experience that currently is held by a small number of long-term participants. These include organizing meetings and building relationships with OMB, OSTP, and Congressional subcommittee staff, and the development and use of WHIPS and other tools. Through documentation, this knowledge base needs to be expanded to more participants and archived for future leaders. (CEF06 Recommendations 4.6)

  Because the users groups have organized the DC Trip, participants have skewed to experimental Energy and Intensity Frontier colleagues. Although efforts are made to achieve broad representation of the community on the trip roster, more needs to be done to ensure representative

participation from segments of our field such as Theory and Computation, from colleagues at all career stages, and from underrepresented groups. (CEF06 Recommendation 4.7)

Finally, opportunities for year-round advocacy should be pursued to engage specific offices (including Congressional local district offices) at other key points in the budget cycle. These opportunities must be weighed against the additional resource costs that would be required. (CEF06 Recommendation 4.8)

3.7.4 Non-Congressional Advocacy

As was mentioned previously, the DC Trip includes meetings with staff from OSTP and OMB. These are the people who provide policy and budgetary guidance concerning science funding to the formulation of the PBR. These meetings are opportunities for HEP to convey the priorities of our field to the Administration, and also for us to learn about the Administration's science priorities. The materials for and timing of the DC Trip are chosen primarily for Congressional advocacy. These choices are not necessarily optimal for Executive branch advocacy. For example, our meetings with OSTP and OMB take place immediately after the completed PBR is released. The potential impact of these meetings is very high, and could be maximized with materials, messages, and timing specifically targeted for these offices.

- **The HEP Congressional advocacy group should work to improve HEP community engagement of the executive branch, especially OMB and OSTP. (CEF06 Recommendation 8)**

No HEP-wide advocacy efforts exist that are directed to state or local governments. However, there are state and local engagement efforts carried out between individual facilities and the communities in which they are located. These include the Fermilab Community Advisory Board which provides community input and feedback to Fermilab regarding its programs and projects, and similar situations exist with Berkeley Lab and SURF. In all cases, these engagements have been mutually beneficial to the facilities and their communities.

- **The HEP Congressional advocacy group and APS DPF executive committee should facilitate discussions to explore the potential advantages to systematic engagement of local and state governments. (CEF06 Recommendation 9)**

3.7.5 Advocacy for Issues Beyond HEP Funding

All of the current HEP community-wide advocacy is directed toward the support and growth of federal funding for HEP. There are many other policy issues not directly tied to HEP funding that nevertheless impact our colleagues and programs of research. Most are or can be addressed with federal legislation. Among these are DEI concerns about limited access to national research facilities for non-R1 institutions, visa and immigration policies that present barriers to foreign scientists wishing to study at or visit US institutions, and balancing research security with open collaboration. While some of these issues are referenced in our DC Trip materials within the context of supporting particle physics, our advocacy infrastructure does not have the resources, procedures, or mandate to advocate for specific non-funding policy positions. Conversations throughout Snowmass on this type of advocacy yielded no consensus between the desire of some to leverage our funding advocacy infrastructure for these issues, and the concerns of others that consensus building

on policy issues and potential negative impacts to the field would prove problematic. However, there are external groups with larger resources, constituencies and infrastructure that we have access to for broader advocacy. Among these are the APS, American Institute of Physics (AIP), and American Association for the Advancement of Science (AAAS). All of these groups employ government relations staff, and possess the resources and experience to mobilize advocacy for non-funding issues. They also run very active Congressional Fellowship programs which offer opportunities for HEP community members to participate in much more direct and deeper government engagement on policy. These opportunities should be much more widely promoted to the HEP community.

- **The HEP Congressional advocacy group and APS DPF executive committee should identify an existing community group or create a new one to take ownership of strengthening connections between the HEP community and science and physics societies, including APS, AIP, and AAAS. (CEF06 Recommendation 6)**

3.7.6 Engagement with Funding Agencies

Another area of government engagement by the HEP community that needs to be improved is direct communication with the funding agencies, DOE and NSF. There are some communication channels that exist, but there are issues with each that prevent them from adequately serving the community. Foremost among the challenges to open communication is the power dynamic between the funding agencies and individual scientists. Groups like HEPAP and the Community of Visitors are explicitly directed to serve as communication channels between the community and agencies, but their memberships are appointed and skewed toward senior colleagues, presenting somewhat of a barrier to younger colleagues feeling comfortable sharing feedback. This is exacerbated by the fact that HEPAP meetings usually have Congressional and/or Executive government officials in attendance. Meetings between DOE/NSF program managers and individual PIs or groups, as well as grant reviews also provide opportunities for communication, but suffer from lack or participation from early career scientists and concerns that negative feedback could have a negative impact on grant applications. None of these channels offers anonymous communication.

- **DOE and NSF should improve existing channels and create new ones, as necessary, to enable HEP community feedback to the funding agencies. (CEF06 Recommendation 7)**

  There are actions that DOE and NSF could take to remove barriers created by the power dynamic between the agencies and researchers, particularly those in early career stages or from marginalized groups. Chief among these are creating anonymous feedback channels and partnering with community leaders such as the users groups, DPF executive committee and collaboration spokespeople to advertise and encourage the use of communication paths. A particular topic of concern that was frequently expressed is the need to open channels of communication regarding details of the granting process and how that process could be improved. (CEF06 Recommendations 7.1-7.3)

3.8 CEF07: Environmental and Societal Impacts

This topical group focused on ideas and projects related to how particle physics research impacts society and the environment. Examples of impacts on society include collaboration between particle physics research

facilities and indigenous communities related with the land host facilities, or ethical usage of software tools in particle physics research. Examples of impacts on the environment range from the local environment of a research facility (pollution, regional development, international visibility, etc.) all the way to the carbon footprints of particle physics research (experiments, facilities, institutions, etc.). Looking at the long time scale of some particle physics experiment proposals, consideration of the implications of climate change and of the various commitments on carbon emissions reductions by host countries is of paramount importance to ensure the success of particle physics research in the future. Ideas and suggestions on all of those issues were encouraged within this topical group.

Ultimately, five contributed papers were developed and submitted this group, on:

- environmental impacts of particle physics [44–46];
- interactions of different laboratories with their local communities [47];
- non-nuclear proliferation [48].

3.8.1 Environmental Impacts of Particle Physics

Particle physics activities include construction and operation of large-scale facilities, detectors, and computing farms, and travels for various types of physics engagements. Doing particle physics impacts on the environment, and this must be considered in the global context of climate change as discussed in Ref. [44]. Future progress in the field will require the construction of new facilities. The environmental impacts of facility constructions to advance particle physics research need to be understood in the global efforts to reduce global warming. The projected carbon impacts of just the construction of the main tunnel of the Future Circular Collider (FCC)—or any similar-scale facility—would be comparable to that of a redevelopment of a major city neighborhood; that level of emission will not go unnoticed. The field needs to invest in carbon reduction R&D and anticipate environmental impact reviews [44]. The green ILC is an effort to include carbon reduction in the design, and later in the construction and operation of this machine; a working group has been organized to study efficient design of ILC components and a sustainable ILC City around the laboratory. Should this machine be constructed, its design will be adapted, in consultation with local authorities, to offset excess carbon emission [8,45]. In Ref. [46], the necessity for environmental sustainability in the development of next generation accelerators is articulated; energy-efficient components and conceptual designs are focus areas for energy efficiency and power consumption in large-scale accelerators. Carbon emissions from greenhouse gases used for detectors and cooling is another area of environmental impact of particle physics activities and mentioned in Ref. [44]. For future particle physics projects, investment in R&D is needed for alternative gases—with low global warming potential—for detector operation and facility cooling, without compromising physics performance. Particle physics research relies on large-scale computing; efforts to mitigate computing-related carbon emission should developed, e.g. by optimizing computing-intensive coding and task scheduling [44]. Greenhouse gas emissions associated to laboratory or university activities are categorized within the scope of direct emissions (from the organization), indirect emissions (electricity, heating, etc.) and other indirect emissions (business travels, commutes, catering, etc.). Across many institutes, much remains to be done to reduce per-capita emissions below the 1 t CO2e per year needed to prevent excessive warming. Travel for physics activities are an essential part of doing particle physics, and aircraft emissions are increasing. It is important to understand what travel are important or necessary and to develop the infrastructures for effective remote engagements. The experiences during the COVID-19 pandemic can serve as guides to optimize in-person versus remote engagements [8, 45]. The following guidelines are advanced to reduce the environmental impacts of particle physics activities:

- New experiments and facility construction projects should report on their planned emissions and energy usage as part of their environmental assessment which will be part of their evaluation criteria. These reports should be inclusive of all aspects of activities, including construction, detector operations, computing, and researcher activities.

- US laboratories should be involved in a review across all international laboratories to ascertain whether emissions are reported clearly and in a standardized way. This will also allow other US particle physics research centers (including universities) to use those standards for calculating their emissions across all scopes.

- Using the reported information as a guide, all participants in particle physics — laboratories, experiments, universities, and individual researchers — should take steps to mitigate their impact on climate change by setting concrete reduction goals and defining pathways to reaching them by means of an open and transparent process involving all relevant members of the community. This may include spending a portion of research time on directly tackling challenges related to climate change in the context of particle physics.

- US laboratories should invest in the development and affordable deployment of next-generation digital meeting spaces in order to minimize the travel emissions of their users. Moreover the particle physics community should actively promote hybrid or virtual research meetings and travel should be more fairly distributed between junior and senior members of the community. For in-person meetings, the meeting location should be chosen carefully such as to minimize the number of long-distance flights and avoid layovers.

- Long-term projects should consider the evolving social and economic context, such as the expectation of de-carbonized electricity production by 2040, and the possibility of carbon pricing that will have an impact on total project costs.

- All US particle physics researchers should actively engage in learning about the climate emergency and about the climate impact of particle-physics research.

- The US particle physics community should promote and publicize their actions surrounding the climate emergency to the general public and other scientific communities.

- The US particle physics community and funding agencies should engage with the broader international community to collectively reduce emissions.

3.8.2 Impact on Local Communities

Physics engagement with local communities is important to build relations and draw long-lasting community support for particle projects and activities; as noted in Section 3.6, successful and impactful engagements should be foundational rather than transactional. In Ref. [47], local community engagement efforts of three laboratories are studied, namely Lawrence Berkeley National Laboratory (Berkeley Lab), Fermi National Accelerator Laboratory (Fermilab), and the Sanford Underground Research Facility (SURF). These laboratories have different local environments, from urban (Berkeley Lab), to suburban (Fermilab), to rural (SURF). In all the three cases, foundational local engagements that promote diversity, communication and lasting relationships, are shown to be mutually beneficial to the community and the laboratory. We propose the following recommendations for foundational engagements between laboratories and their surrounding communities.

Laboratories should engage with their local communities in order to create awareness about their work and build lasting, positive relationships. Community engagement plays an essential role in local decision-making, building relationships, and important discussions about the implementation of key projects. Large particle physics projects funded by the US Government require an evaluation and mitigation of each project's potential impacts on the local communities. In addition to satisfying governmental requirements, working alongside their local communities can foster lasting change that broadens the positive societal impacts of particle physics research.

Laboratories should have consistent outreach and engagement efforts that provide regular opportunities for feedback to help establish trust. Through its Community Advisory Board, Fermilab offered regularly scheduled meetings to gain feedback from local communities. In addition, SURF ensured its communication with stakeholders at Isna Wica Owayawa was consistent and persistent in order to overcome scheduling and other barriers.

Laboratories should promote diversity of membership and collaborative efforts in their outreach initiatives to bring a variety of perspectives to the table and create a better end project. SURF's work with tribal elders and other leaders in its local community helps ensure perspectives of indigenous populations in the region are represented and reflected in the work of the Sacred Circle Garden. Meanwhile, Fermilab regularly refreshes and expands its CAB membership to ensure it remains representative of the diversity of its suburban area.

Laboratories should avoid transactional relationships when developing relationships with stakeholders, and instead focus on approaches that provide value to each entity. Laboratories will be best served by making an extended commitment to working with collaborators over an extended period of time, rather than one-time interactions. Opportunities to receive feedback and consider changes can have lasting impacts on the collaborative efforts. SURF has continued to see improvement in program outcomes with Isna Wica Owayawa using this approach. Berkeley Lab has seen success by utilizing small investments in staff time, small-scale donations, and other resources as a launch pad for lasting collaborations with organizations with shared goals and values.

Laboratories should utilize methods that promote honest, two-way communication when engaging in collaborative efforts with stakeholders. All three case studies exemplify the benefits of open communication.The CAB at Fermilab creates a space where local community members and the lab are able to air concerns and discuss solutions. Berkeley Lab ensures that its community engagement interactions provide a space for members of the community and partners to voice their opinions, while Berkeley Lab listens and reflects on the opinions shared. Finally, SURF seeks indigenous perspectives although in some instances, the resulting dialogue can result in uncomfortable conversations. However, by promoting difficult conversations in a safe environment, SURF was able to promote a design for its ethnobotanical garden that was approved by all involved.

3.8.3 Impact on Nuclear Non-proliferation

Detector technologies for neutrino physics can find applications—or benefit from R&D—in nuclear non-proliferation where detection of reactor anti-neutrinos offer promising reactor monitoring systems that can be remotely operated, robust, non-intrusive and persistent. These ideas are explored in Ref. [48] and the following recommendations are advanced:

The High Energy Physics community should **continue to engage** in a natural synergy in research activities into next-generation large scale water and scintillator neutrino detectors, now being studied for remote reactor monitoring, discovery and exclusion applications in cooperative nonproliferation contexts.

Examples of ongoing synergistic work at US national laboratories and universities should continue and be expanded upon. These include prototype gadolinium-doped water and water-based and opaque scintillator test-beds and demonstrators, extensive testing and industry partnerships related to large area fast position-sensitive photomultiplier tubes, and the development of concepts for a possible underground kiloton-scale water-based detector for reactor monitoring and technology demonstrations.

Opportunities for engagement between the particle physics and nonproliferation communities should be encouraged. Examples include the bi-annual Applied Antineutrino Physics conferences, collaboration with US national laboratories engaging in this research, and occasional NNSA funding opportunities supporting a blend of nonproliferation and basic science R&D, directed at the US academic community.

3.8.4 Links with Other Topical groups

This topical group is interlinked with other Community Engagement Frontier topical groups. For example, the impacts on society include issues involving inclusion and diversity and the impacts on the environment and the sustainability of the field involve components associated with the applications and industry topical group.

3.9 Conclusions

During Snowmass 2021, participants in the Community Engagement Frontier have attempted to address the importance of engaging members of various communities to generate support for and sustainability of high energy physics. The CEF efforts were organized into seven topical groups and connections with the other Snowmass frontiers were established through frontier liaisons to exchange feedback. Each CEF topical group studied specific focus areas of engagement and their importance to society and the future of our field. The focus areas were Applications and Industry, Career Pipeline and Development, Diversity, Equity and Inclusion, Physics Education, Public Education and Outreach, Public Policy and Government Engagement, and Environmental and Societal Impacts. Topical groups collected and studied inputs from letters of interest, surveys, town hall meetings, workshops, invited expert discussions, and regular working group meetings. These efforts produced thirty-five contributed papers and seven topical group reports containing recommendations to improve engagement between HEP and related communities. A few ideas that were not developed into contributed papers because of lack of person-power are nevertheless noted in the texts. To facilitate maximum impact and efficiency of implementation, the suggested recommendations for action have been directed to different entities within the HEP community, namely government and funding agencies, academic and research institutions, research collaborations, professional societies and individual physicists, and have been organized into overall goals categorized by five target communities for engagement.

We, the topical group and frontier conveners of CEF, lament the persistently low participation in community engagement. Regrettably, regardless of efforts throughout Snowmass 2021 to motivate participation on cross-cutting CEF issues, the work in this frontier was carried out by a relatively small number of colleagues, most of whom are physicists who also had interests in other physics frontiers that they were largely unable to pursue. Various reasons, some quite understandable, have been advanced to explain this lack of interest. However, until due importance is given to community engagement efforts and mechanisms are implemented for support, encouragement and rewards, no meaningful progress will be achieved in spite of expressed well-meaning intentions. We call upon each specified entities' members that are serious about improving HEP community engagement to take ownership of the CEF suggestions and act on their implementation within

structures developed to foster and gauge progress. We hope that at the next Snowmass, we do not find a repeat of this past decade's inaction on these issues, but rather that we inherit a vibrant program of HEP community engagement on which to build.

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4

Computational Frontier

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Executive Summary

Software and Computing (S&C) are essential to all High Energy Physics (HEP) experiments and many theoretical studies. The size and complexity of S&C are now commensurate with that of experimental instruments, playing a critical role in experimental design, data acquisition/instrumental control, reconstruction, and analysis. Furthermore, S&C often plays a leading role in driving the precision of theoretical calculations and simulations. Within this central role in HEP, S&C has been immensely successful over the last decade. Every experimental result and many theoretical insights were only possible due to advances in S&C. We have developed innovative solutions to unique HEP S&C challenges and when possible, we have embraced community standards in software packages, versioning tools, etc. Grass-roots initiatives such as the HEP Software Foundation (HSF) [1] have unified parts of the community in these efforts. A number of successful cross-cutting S&C research centers and institutes have also emerged to enhance HEP science.

Additionally, limited computing resources have gone much further than anticipated due to methodological innovation. Part of these advances are driven by increased use of computing hardware heterogeneity and specialization, as well as increased use of high-performance computing facilities. HEP is a significant user of national supercomputing facilities through large and small [34] particle physics and cosmology experiment and simulation workflows, other areas of theory (predominately lattice field theory), and accelerator modeling. Significant progress has been made within these communities to adapt software applications for effective use of hardware accelerators, and in preparation for future exascale computing resources. Examples of funded programs in this area include the DOE Exascale Computing Project (ECP), Scientific Discovery through Advanced Computing (SciDAC), the Center for Computational Excellence (CCE), Computational HEP more generally, and the NSF Institute for Research and Innovation in Software for HEP (IRIS-HEP).

Furthermore, the deep learning revolution that started in the last decade is already having a widespread impact on all aspects of HEP. Quantum computing has emerged as a technology that may enable the study of various quantum systems that are beyond the capabilities of classical tools. Neither of these topics was considered in the last Snowmass planning process from 2013 and, in both areas, HEP scientists are making contributions well beyond our field.

The goal of Snowmass is to provide input for the Particle Physics Project Prioritization Panel (P5) with a ten year timescale. While S&C is clearly an enabler of the HEP science drivers, it is not managed like a 'project' as in the case of facilities, experiments, and surveys. S&C is no less important, often transcends traditional boundaries, and changes on a much faster timescale than Snowmass processes. For this reason, we have identified one central recommendation for the 2021 Snowmass:

We recommend the creation of a standing **Coordinating Panel for Software and Computing (CPSC)** under DPF, mirroring the panel for advanced detectors (CPAD) established in 2012.

> *Purpose: Promote, coordinate, and assist the HEP community on Software and Computing, working with scientific collaborations, grassroots organizations, institutes and centers, community leaders, and funding agencies on the evolving HEP Software and Computing needs of experimental, observational, and theoretical aspects of the HEP programs. The scope should include research, development, maintenance, and user support.*

Further details of the community vision for the CPSC can be found in the body of this report.

Continued S&C support for facilities, experiments, surveys, and theoretical calculations is essential for the health of the HEP science program. This includes S&C personnel as well as computing power, storage, and networking. We have identified four key areas of need, listed below, where increased investment would significantly enhance the physics output of the US HEP community.

Computing is a **global endeavor** and addressing the above items should include **coordination with worldwide partners**. We also strongly support continued, significant investment in emerging technologies including quantum computing and machine learning, which were not part of the 2013 Snowmass process.

1. The US HEP community should take a leading role in **long-term development, maintenance, and user support** of essential software packages with targeted investment.
   - A new structure is needed to fund modernization, maintenance, and user support of existing tools (grants typically only fund ground-breaking R&D or development of new software).
   - Examples include (i) event generators and simulation tools like `Geant4` [2–4] that do not belong to a particular facility, experiment, or survey, (ii) S&C tools associated with one or more experiments, and (iii) data/software preservation after an experiment has ended.

2. Through existing, reshaped, and expanded programs, R&D efforts **cutting across project or discipline boundaries** should be supported from proof of concept to prototype to production.
   - Computational HEP is a vehicle for cross-cutting R&D. Supporting research in this area at a variety of scales would be broadly impactful.
   - Examples include S&C for theoretical calculations/generators; cosmological, accelerator, and detector modeling; machine learning methodology and hardware ecosystems; and algorithms and packages across experiment boundaries.

3. Support for computing professionals/researchers and physicists to conduct code re-engineering and adaptation will **enable us to use heterogeneous resources** most effectively.

- Most HEP software runs on a single computing platform, making it difficult to use the multitude of hardware accelerators and diverse computing resources like cloud, HPC, etc.
- To satisfy the needs of inherently serial algorithms that are still transitioning towards computing accelerators or are not cost-effective to port, an appropriate level of traditional CPU-based hardware should coexist with more powerful heterogeneous resources.

4. Strong investment in **career development** for HEP S&C researchers will ensure future success.

- Sustainable efforts in computation require continual recruitment and training of the HEP workforce. We need to create an environment that is inclusive, supportive, and welcoming in order to integrate diverse skill sets and experiences.
- Successful training events have been carried out through HEP experiments, institutes/organizations, and growing numbers of university courses. We need to continue and grow these efforts for documentation and training at multiple levels.
- Faculty/staff positions for physicists with expertise in S&C for HEP are scarce and person-power shortfall in this area endemic. Funding agencies can catalyze faculty-level appointments in S&C with joint appointments at national laboratories.

Additional details for all of the above points can be found in the body of this report.

4.1 Introduction

The Computational Frontier is different from many of the other frontiers that are part of the Particle Physics Community Planning Exercise ("Snowmass"). For a number of the other frontiers, the goal is to identify large scale, long running projects that will be carefully considered by the Particle Physics Project Prioritization Panel (P5). Our frontier, however, is important to almost all the other frontiers in that software and computing are ubiquitous in experiment and of essential importance in many areas of theoretical physics. Two of the top ten most highly-cited papers of all time in particle physics[1] (according to INSPIRE) are software programs [2, 5]. If we get the computing challenges right, the scientific output will follow. If not, computing costs will be inflated or our productivity will suffer, and for some projects, it will suffer greatly. For example, computing limitations (e.g., in terms of the ultimate precision) are on par with detector limitations in many flagship experiments — without computing/methodological innovation, we will not be able to take full advantage of pristine data collected by state-of-the-art instruments.

Another difference between computing infrastructure and a large experimental detector is that the latter often relies on custom or bespoke hardware, some of which may be expected to work for decades. Computing hardware, on the other hand, is often replaced after half a decade (or less) and it is not yet clear what the next devices will look like. However, the software in use in our community can last for decades, although it evolves over time. In fact, over the last decade or so, changes in computer hardware have presented a major challenge to software development. The issue of how to deal with heterogeneous nodes employing various hardware accelerator technologies does not have a single solution. At this point, it is not clear which of several approaches will prevail, or even if there will emerge a single dominant approach. This complicates the already challenging task of training for modern software development. Coping with a rapidly evolving hardware environment is one of many challenges we investigate in this report.

[1] N.B. these are also only specific versions of these programs - the citation count is much higher if all versions are included.

Despite differences between computing and instrumentation, there are also close connections. Extracting physics from detectors requires experimental algorithms, simulations, and other software and computing tools. For detector simulations and reconstruction algorithms, these tools are often tailored to specific instruments. Even though traditionally, hardware is designed independent of software (which usually comes later), there is a growing movement towards codesign at all levels in order to maximize the physics output and minimize costs. For example, certain detector design choices may lead to computationally expensive simulation and reconstruction algorithms that may reduce the physics output volume and quality in practice and require increased investments in computing resources. Furthermore, the physics sensitivity may even be enhanced with automated software algorithms, such as those based on machine learning. Codesign is relevant for all areas of HEP, including theory (such as computing hardware and lattice gauge theory) and quantum information science (for HEP-tailored quantum computers).

Our goal is to examine the software and computing needs of the particle physics community over the next 10 years, with a 20 year global vision for the field. Within this timeframe, there will be a spectrum of experiments, surveys, accelerator R&D, and theoretical efforts that will stress the community computational resources. Figure 4-1 provides a brief characterization of some aspects of this challenge for big experiments across frontiers. For example, the High-Luminosity Large Hadron Collider (HL-LHC) will run through the 2030s and its experiments produce an order of magnitude more data than during the initial LHC period. Online (low-latency or sometimes, 'edge') computing will become more prevalent and require various hardware accelerator systems to deliver low-latency decisions. The cosmic and neutrino frontiers are not far behind the energy frontier in terms of data size. Not captured by these numbers is the immense computational resources required for generating simulated data that are critical for theoretical predictions and data analysis. We have mostly focused on the upcoming decade, where we need to address a resource gap of near-future programs and to account for the rapidly evolving technologies that make predictions beyond 2035 inaccurate. However, we also appreciate and consider the near-term R&D program required to prepare for future facilities.

Software and computing have long been central to the HEP science program and therefore played a key role in the the 2013 Snowmass report [6], but there are many new features of the frontier in this round. The 2013 report was mostly organized along physics applications, with subgroups dedicated to computing for the Cosmic Frontier [7], Energy Frontier [8], Intensity Frontier [9], Accelerator Science [10], lattice field theory [11], and perturbative field theory [12]. Additional subgroups covered cross-cutting topics related to distributed computing and facilities infrastructure [13], networking [14], software development, personnel, and training [15], and storage and data management [16]. For this round, we have forgone any organization by frontier and instead, we have set up topical groups that are only cross-cutting in nature. This reflects the growing need for shared solutions to computing challenges that are not dominated by any one frontier. To this end, the 2021–2022 Snowmass Computational Frontier (CompF) is organized into seven topical groups.

The first topical group (CompF1) examined **Experimental Algorithm Parallelization** [17]. Functional areas of this topical group include parallelization of detector reconstruction algorithms, physics object reconstruction/calibration algorithms, hardware utilization (including accelerators), developing better algorithms in addition to parallelization, and portability solutions that support the same algorithm implementation on multiple hardware architectures. This includes software frameworks used for such tasks.

The second topical group (CompF2) covered **Theoretical Calculations and Simulation** [18]. This includes standalone perturbative and lattice calculations as well as theory calculations that are embedded in event generators. Additionally, CompF2 considered detector simulations, particle accelerator simulations, and cosmic frontier simulations. A cross-cutting issue was the utilization of hardware and the adaptation of software to hardware accelerators to take advantage of heterogeneous computing resources.

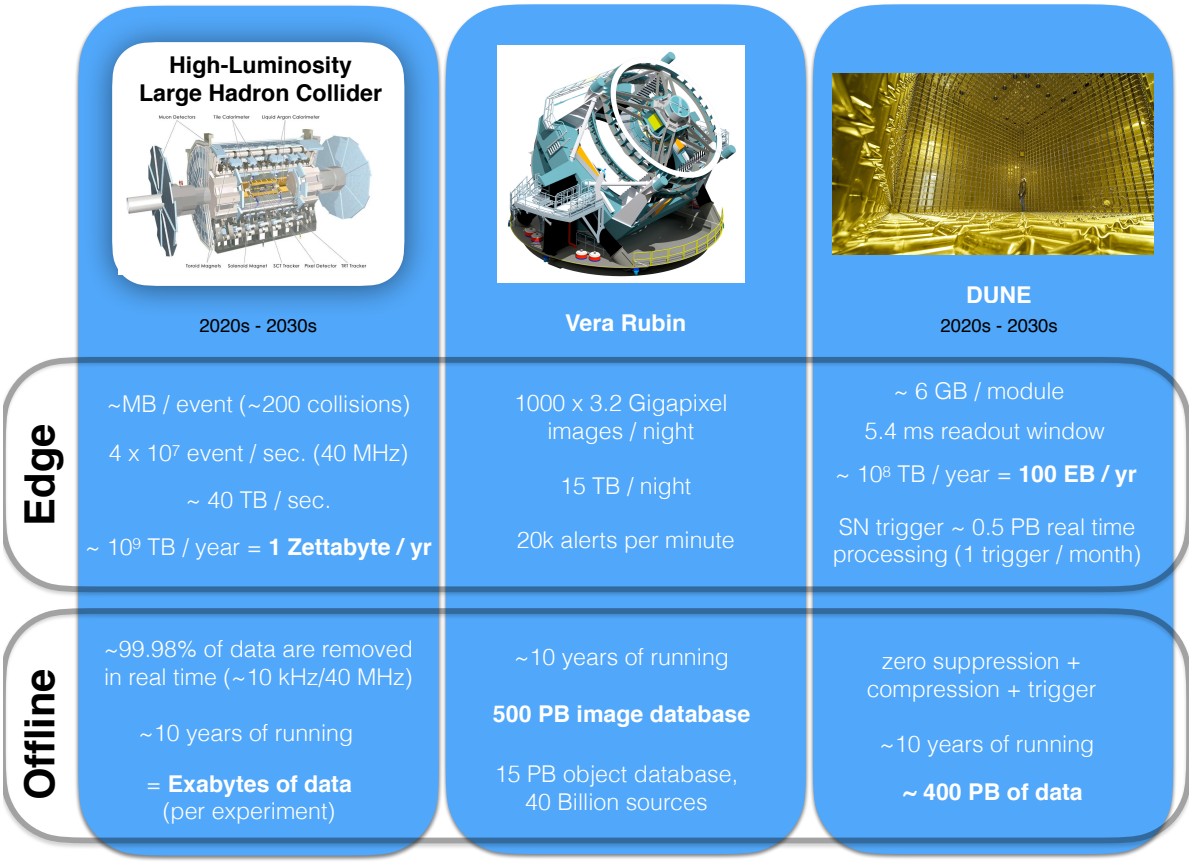

Figure 4-1. *An overview of the online (low-latency or sometimes, 'edge') and offline (high-latency) computing requirements for large experiments/surveys in the energy frontier ATLAS/CMS), cosmic frontier (Vera Rubin), and neutrino frontier (DUNE) over the next decade. These are not all experiments/surveys and the numbers are meant only to be illustrative. Furthermore, the challenges faced by many smaller experiments are not simply captured by such numbers. See the rest of the report for further details.*

Topical group three (CompF3) explored **Machine Learning** [19]. While multivariate analysis has been commonplace in particle physics for decades, modern machine learning has revolutionized everyday life and is poised to make paradigm-shifting contributions to particle physics. Machine learning was essentially not a part of the 2013 report and so it is an emerging technology that has rapidly become a mainstream component of software and computing in particle physics. CompF3 was tasked with understanding the development of methods and the deployment of machine learning methods at both small and large scales as well as in online and in offline settings.

A fourth topical group (CompF4) studied **Storage and Processing Resource** Access [20], also known as Facility and Infrastructure Research and Development (R&D). Functional areas of CompF4 include access to data for large scale central workflows as well as end user analysis, access to high- and low-latency storage, access to CPU resources and various hardware accelerators, including specialized machine learning hardware, and the interconnection of these topics through networking. While HEP has a long history of maintaining and utilizing centralized and distributed computing facilities, there is now a growing diversity of options. High Performance Computing Centers (HPCCs) are becoming more heterogeneous, enabling and complicating experimental and theoretical workflows. At the same time, the commercial cloud has significantly grown in capacity and accessibility which may open up the possibility of supplementing a non-trivial fraction of HEP computing.

The fifth topical group (CompF5) investigated **End User Analysis** [21]. This includes the development and utilization of analysis facilities as well as software topics related to analysis libraries (including ROOT [22]), data storage formats, dataset bookkeeping, programming languages, software collaboration tools, and low- and high-latency analysis. Since the last Snowmass, there has been a large transition from `C++`-based analysis to `python`-based analysis (see e.g., Ref. [23]). Additionally, the tool ecosystem has diversified due to the prevalence of excellent (non-HEP) community packages like `SciPy` [24]. The HEP community is at a crossroads where we must decide to what extent we will maintain custom software for generic analysis or how much we will turn to or integrate (and contribute to) broader community standards into our workflows.

Topical group six (CompF6) covered **Quantum Computing** [25]. Like machine learning, quantum computing was not part of the 2013 Snowmass process. Due to rapid advances in algorithms and hardware, quantum computing has become a rapidly growing research area within high energy physics. While fully error correcting quantum computers do not yet exist, noisy near-term devices still provide an exciting testbed for algorithm development. The goal of CompF6 was to investigate the potential impact of quantum computing on particle physics and to determine what resource investment is required in the near term to explore the mid- and longer-term potential of quantum computing for HEP. There is an intimate connection between quantum computing and other areas of Quantum Information Science (QIS), which are covered in other frontiers (TF10 in Theory and IF1 in Instrumentation).

Lastly, a seventh topical group (CompF7) explored **Reinterpretation and Long-term Preservation of Data and Code** [26]. This includes how/where various data products are accessed/stored. Data products vary from the highly synthesized content of papers (including digitized figures) to the relatively raw public data that can be used for generic data analysis. Central to this topical group are the tools for generating annotated public data and software, for combining results across experiments/surveys, and for archiving/re-running analyses (long) after the original research.

Not all topics are covered by our topical groups. For example, training and career development as well as diversity and climate are cross-cutting challenges that are relevant for all topical groups. There are also a number of topics that are shared between topical groups such as machine learning hardware at high performance computing centers (CompF3 and CompF4). The topical group reports from this Snowmass process cover such topics from different viewpoints in order to explore cross-cutting challenges from the various stakeholders.

Before proceeding to the content of our report, it is useful to put the work of our frontier in the a global context. Preceding this Snowmass process by a couple of years was the latest European Strategy Report [27, 28]. Software and computing are prominently featured with recommendations such as:

> *Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.*
>
> (...)
>
> *Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programmes. The community faces major challenges in this area, notably with a view to the HL-LHC. As a result, the software and computing models used in particle physics research must evolve to meet the future needs of the field. The community must vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry, to develop software and computing infrastructures that exploit recent advances in information technology and data science. Further development of internal policies on open data and data preservation should be encouraged, and an adequate level of resources invested in their implementation.*
>
> (...)
>
> *Particle physics, with its fundamental questions and technological innovations, attracts bright young minds. Their education and training are crucial for the needs of the field and of society at large. For early-career researchers to thrive, the particle physics community should place strong emphasis on their supervision and training. Additional measures should be taken in large collaborations to increase the recognition of individuals developing and maintaining experiments, computing and software.*

Unsurprisingly, the recommendations of our frontier resonate with the European Strategy, with more details provided in the Executive Summary and Sec. 11.

4.2 Experimental Algorithm Parallelization

Within HEP, experimental algorithms refers to elements of software developed to, for example, reconstruct physics objects (e.g., electrons, photons, muons, neutrinos, jets of hadrons, etc.), process observational data, and perform their calibration. Future experiments and cosmological observations will see a substantial increase in the volume of data collected, as compared to current programs. Additionally, the improvement of detector capabilities will have a significant impact on experimental algorithms, demanding more computing power and data storage in a world of flat budgets, where growth in resources will depend on the expected reductions in the cost of hardware. Although the focus of HEP experiments is typically high-throughput computing (HTC), in many cases provided by grid and local computing clusters, hardware evolution is prompting the community to increasingly utilize hardware-accelerated systems, which dominate High Performance Computing (HPC) facilities. These facilities are large US government investments which are being made increasingly available to the HEP community, while computing resources specifically dedicated to HEP become scarcer. Cosmic surveys and the accelerator modeling projects offer a good example of effective use have used HPC resources, having utilized leadership computing facilities for many years to carry out a large fraction of their simulation work.

In most HEP scientific programs, the challenges presented by the increase in data volumes, as well as the rapid evolution of the computing landscape, compound with the time constraints imposed by the slow development

cycles of experimental software, which is particularly acute in large collaborations. Consequently, the opportunities presented by emerging technologies, including HPCs and hardware specifically designed for AI/ML applications, offer the chance to bridge the gap between computing requirements and available resources. Success will, however, require continuous and significant R&D investments during the next 10 to 15 years. The R&D program will seek to explore performance portability techniques to support multiple computing architectures while minimizing platform-specific code with minimal impact in performance. This program will also integrate AI/ML methods to tackle the analysis of complex data-sets to improve or preserve physics performance while reducing computational costs, and build computational frameworks that allow for collaborative software development.

Technology evolution will continue to demand significant investment in software frameworks within experiments, as algorithms are adapted to modern computing paradigms. In addition to parallelism on multi- or many-core CPUs, frameworks need to support execution of algorithms on heterogeneous platforms, including CPUs, GPUs, and field programmable gate arrays (FPGAs). Frameworks designed for multiple experiments, as well as common reconstruction tools, could significantly save resources by reducing code duplication. Common tools can provide ready-to-use software solutions, as well as a platform for R&D work spanning usage of AI/ML methods, algorithm parallelization, and deployment at HPCs. This strategy would reduce the workload of individual collaborations, and benefit small experiments.

In the particular case of hadron collider experiments, a critical challenge is to improve, or at least maintain, the physics performance of reconstructed physics objects in the context of growing numbers of hard collisions recorded in an event (pileup), as well as increased detector complexity. Additionally, charged particle trajectory reconstruction (tracking) is particularly expensive computationally and will benefit from more parallelism and the use of accelerators in heterogeneous platforms [29]. AI/ML has shown its power for physics object identification and has the potential to play an even larger role in particle reconstruction at future experiments. A convergence of trigger and offline algorithms, traditionally cruder and faster in triggers, seems feasible for the first time in history given the opportunities offered by hardware accelerators, such as GPUs.

The field of cosmology has undergone a major transformation over the last two decades due to the advent of large sky surveys. For optical surveys, the algorithms can be broadly classified as falling into two classes: algorithms for static science where the data is collected over a long span of time, and time domain science, where algorithms are needed to find events quickly, classify them and provide guidance for further follow-up actions. In both cases, AI/ML algorithms and heterogeneous computing can play an important role, given the necessary forethought and support [30]. In CMB experiments, the primary computational challenge is reduction of the large raw detector data to intensity and polarization maps, and then simulation of the instrument and map-making strategy. This will require use of accelerators and exploitation of a variety of computing systems, including HPCs and distributed resources. Direct dark matter detection experiments face a different set of challenges with regard to experimental algorithms than the cosmological surveys. Current experiments are approaching data volumes of $\sim$1 PB/year, see, e.g., Ref. [31]. Their challenges more closely mirror those of collider physics experiments in what relates to the use of HPC resources and scalable HEP frameworks, as well as AI/ML techniques.

Experimental algorithms for neutrino experiments, and, in particular, for liquid argon time projection chamber (LArTPC) detectors, can be divided in two big categories: signal processing and high-level algorithms. Signal processing algorithms operate on the waveform signal from the TPC. Higher level algorithms rely on the signal processing for physics object clustering and identification, including tracking, calorimetry, and particle identification tasks. Different methods are being employed by experiments or investigated in the context of more general R&D projects, using techniques which span from traditional algorithms to deep learning. Computing challenges arise from the large amount of raw data for a full event readout, imposing stringent demands on memory usage and disk space [32]. Parallel processing patterns must

continue to be employed, using both CPU-only resources and mixed CPU-GPU. Software packages such as the Wire-Cell Toolkit [33], designed for highly multi-threaded operations, must continue to be improved and supported. Continuous development of the common LArSoft library is vital to enable direct sharing of developments across currently operating LArTPC experiments [34]. R&D to run data processing tasks for neutrino experiments at HPCs exploiting optimization features at the node level, such as vectorization and multi-threading, need to be undertaken.

Experiments targeting rare events are also implementing algorithms to run on heterogeneous architectures, including at the trigger level, achieving significant savings in computing power. This path has been followed by experiments exploring flavor physics as well as muon experiments.

All these challenges presented by experimental algorithms across physics frontiers call for a common set of recommendations:

- Workable solutions must be found to exploit **heterogeneous computing platforms**. Portability solutions must be developed and supported. In parallel, targeted optimizations of key algorithms for experiments often provide the largest speedups and must be supported.
- **Software frameworks and common tools** must evolve and adapt to the new computing landscape to enabling the usage of parallel algorithms in production environments of big and small experiments.
- **Interdisciplinary collaborations and programs** should play a critical role in developing algorithm approaches to take full advantage of emerging hardware and software technology.
- **Training opportunities** for early-career researchers are essential to ensure that the experiments acquire the necessary expertise to utilize these technologies.
- **Career opportunities** targeting researchers who focus on experimental algorithm development need to be created. The scientific value of this work is typically not fully appreciated in faculty and staff searches.
- To enable long-term sustainability of HEP software products and offer job security to researchers in this area, **software development should be supported** according to a model similar to that for detector projects, or directly made part of detector projects. Funding needs to go beyond the R&D phase of algorithm and software exploration and into the development, production, and maintenance phases.
- Funding agencies and research teams have to commit **sustainable long-term effort to mission-critical software products**.
- Big experiments/surveys need **multi-year computing resource allocation planning** for use of national facilities, as an alternative to the current model of annual allocations.

4.3 Theoretical Calculations and Simulation

Theoretical calculations and simulation overlap with almost all aspects of HEP and almost every Frontier. The topic is very broad and was divided into six domains for the purpose of this report: cosmic calculations, particle accelerator modeling, detector simulation, event generators, perturbative calculations, and lattice quantum chromodynamics (QCD). Computational challenges are different across these domains. For instance, accelerator simulations require a highly coordinated interplay of several tasks, which benefit from

fast inter-node connections available in HPCs, while matrix element calculations for different phase space points in event generators are completely independent of one another and can be executed in separate nodes in a computer network, including HPC facilities. Nonetheless, we have identified significant commonality in computing needs among the six areas, which we list alongside those specific to a domain.

- **Hardware accelerator-friendly, portable common tools** are essential to adapt common software packages to run efficiently on hardware accelerators, including GPUs, and should continue to be supported with sufficient effort to deliver complete products and incorporate portability solutions to support different coprocessor devices and architectures.
- **Universal programming interfaces** would remove barriers to portability and return on investment in software.
- **Early access to new computing hardware** is a key element to ensure timely scientific exploitation.
- **Right-sized CPU clusters** are necessary to provide general purpose computational cores with high performance memory for important algorithms that do not easily map to computational accelerators.
- **Automation of memory hierarchy** would remove the significant burden of explicitly moving data between different levels of the memory hierarchy, avoiding a real drain on scientific programmer productivity.
- **Best practices for common software** should be encouraged to ensure interoperability and common data structures. Existing standard libraries and underlying software technologies should be used when available and feasible.
- New processes and organizations should be established with funding agencies for **long-term software maintenance and support of common software tools** in the areas of accelerator modeling, detector simulation, and physics generators must be strengthened.
- **Collaboration with communities of computer scientists, applied mathematicians, nuclear physicists and others relevant to HEP computational and physics model development efforts** should continue to be supported and encouraged in the context of DOE and NSF programs designed to create common computing and simulation infrastructure, as well as to achieve effective utilization of U.S. resources across scientific fields.
- Programs of **joint lab-university tenure track appointments in the area of S&C** should be created with the goal to help universities build strong research groups focused on topics of S&C for HEP, while generating academic opportunities for young researchers in that area.
- **Training** in both novel architectures and AI/ML with a low barrier to access for graduate students, postdoctoral researchers, and domain scientists is critical to ensuring the skills base exists for productive science in theoretical calculation and simulation.

4.3.1 Cosmic Calculations

In order to successfully achieve the observational goals, a state-of-the-art simulation and modeling program is needed [35]. Cosmological simulations provide an invaluable tool to optimize the observation design, to interpret observation data, and to help unearth the underlying physics. Next-generation cosmological

simulations will increasingly focus on physically rich high-fidelity simulations that can directly connect with observational outputs from multiple different surveys.

Several types of cosmological simulations are employed. The first-principles N-body simulations that have no free parameters can accurately describe dark matter fluctuations from the largest observable scales down to scales deep into the nonlinear regime. Additional models such as the halo occupation distribution, sub-halo abundance matching, or other schemes are added on top of a simulation to reconstruct galaxies. Hydrodynamical simulations provide a reasonably accurate description of the distribution of baryons, quantify the effects of baryons on various probes of large-scale structure, and provide useful results for the distribution and properties of galaxies and clusters.

The diverse observational probes present significant challenges in cosmological simulations. One challenge is the computational cost to include multiple probes with high precision. In addition, computationally demanding hydrodynamical simulations are required to simulate some observables such as the thermal and kinetic Sunyaev-Zel'dovich effects, tSZ and kSZ, to infer the distribution of gas in the universe, or Lyman-α, to constrain thermal properties of the intergalactic medium. Semi-numerical simulations are used when the hydrodynamical simulations cannot cover large enough volume while reaching small enough halos. Another challenge for cosmological simulations is to reproduce observations, for example, correlations between multi-wavelength observables, in consistent galaxy formation models. It is necessary to develop simulation models that can be applied to gravity-only simulations and account for correlations between neutral and ionized gas, stars, and dust in galaxies and galaxy clusters. Also, it is not trivial to simulate massive neutrinos since they make up a non-negligible fraction of the total energy but can be decoupled when relativistic and have a free streaming scale. In the N-body simulations, thermal velocity distributions need to be accounted for in the structure formation calculation on smaller scales. Covering both the large volume required by the weak lensing and maintaining the accuracy at small scales required by strong lensing presents another computational challenge in ray tracing. In the modeling for future analyses of small scale measurements, baryonic feedback effects that can change the local matter density must be included in the cosmological simulations. There is also the need to include models of modified gravity for dark energy studies, as well as a variety of dark matter models (warm dark matter, interacting dark matter, self-interacting dark matter, ultralight dark matter, ultraheavy dark matter, multiple component dark matter [36]). Additionally, neutrino experiments demand modeling of supernovae. Next-generation cosmological surveys demand better understanding, mitigation, and control of systematic uncertainties using realistic "virtual universes" from cosmological simulations.

Cosmological simulations are computationally intensive and demand the use of state-of-the-art computer hardware. With the arrival of exascale supercomputers, cosmological simulations will need to use computer accelerators and memory access patterns effectively, as well as performance portable programming models and scalable algorithms. Scalable analysis approaches are of utmost importance, since the handling and processing of large simulation data sets require large computing resources in their own right. Furthermore, co-development of simulation software and analysis tools is recommended for a successful cosmological simulation program.

4.3.2 Particle Accelerator Modeling

Particle accelerators are large and complicated scientific devices that can be thousands of meters long with hundreds of thousands of elements. Their design, construction and operation are both sophisticated and expensive, and depend critically on computer modeling. To meet the needs of next-generation accelerators, it is important for modeling tools to include all types of accelerating structures (e.g., RF-based, plasma-

based, structured-based wakefield, plasmonic) and different accelerator components (e.g., superconducting magnets, structured plasmas), and to target the accelerator and beam physics thrust grand challenges on intensity, quality, control, safety, and prediction.

The final particle beam quality delivered by particle accelerators depends on the performance of the entire accelerator system, consisting of many different segments. To attain an optimal design, end-to-end simulations starting with the source and ending at the target or the interaction region are needed. These simulations should include first-principles models for high precision accelerator design and fast machine learning-based surrogate models for online particle accelerator tuning. Such a virtual particle accelerator can be used as an emulator of the real physical accelerator in the accelerator operation. One challenge in the end-to-end simulation is to transfer particle data from different components of the particle accelerator [37]. High-fidelity end-to-end accelerator simulation is computationally very expensive, especially when including collective effects, with run times varying from days to months. Cutting-edge and emerging computing techniques including advanced algorithms, AI/ML methods, and quantum computing may substantially reduce the computational time and enable a fast real-time optimization with end-to-end simulations. Advanced algorithms play an important role in accelerator modeling. High-fidelity self-consistent simulations cannot be achieved without advanced algorithms, which can lead to significant improvements in computational speed [38, 39]. R&D is needed to explore new algorithms that exhibit better properties, remove the bottlenecks in existing algorithms on cutting-edge heterogeneous computing hardware (e.g., GPU, FPGA), and improve their speed and accuracy. Differentiable simulations show great potential to reduce the number of simulations needed for optimization and design. Using AI/ML surrogate models of the physics simulation can save orders of magnitude computing time [40]. Support is needed for the development of AI/ML modeling techniques and their integration into accelerator simulation and control systems, with an emphasis on continual and adaptive learning for time-varying systems, uncertainty quantification, and physics-informed methods to enable broader model generalization to new application conditions.

Particle accelerator modeling is computationally intensive and has utilized supercomputers for many years. It has used both high-performance computing to model collective effects and high-throughput computing to model single particle dynamics. On exascale supercomputers and special purpose computers with hardware accelerators (e.g., GPUs), it is a challenge to achieve the supercomputer peak performance due to deep levels of independent memory caches, on top of global and neighboring communications that are used to exchange information across multiple computer nodes during the simulation. As part of this, the workload needs to be uniformly distributed among many compute units to achieve good parallel efficiency. Support is needed to adopt portable, state-of-the-art programming paradigms and frameworks that support both multi-level parallelization and effective dynamic load balancing over all levels of compute parallelism, so that simulations run efficiently on computer architectures with scalable I/O, post-processing and in situ data analysis solutions. Furthermore, it is desirable to organize the beam and accelerator modeling community in open efforts to foster the development of ecosystems of interoperable codes and tools, libraries and frameworks, based on API and data standards, establish open access data and workflow repositories, and have an organized governance structure. Finally, support for development, maintenance, data-driven validation, user support and training are essential to guarantee sustainability, innovative potential and reliability of particle accelerator simulation.

4.3.3 Detector Simulation

Accurate detector simulation is crucial for tasks ranging from detector design to data analysis [41]. `Geant4` [2–4] is the primary tool used for detector simulation throughout HEP [42]. The `Geant4` collaboration and the HEP community engage in continuous research and development to improve the computational performance,

refine the models of physical interactions, and incorporate new technical features and models. `Geant4` is the center of an ecosystem that includes numerous software packages serving different needs. This includes material modeling and geometry navigation, the physics of the interaction of particles with matter, as well as fast simulation engines and prototypes to execute tasks on GPUs.

The next generation of collider experiments, including the HL-LHC and the various future colliders proposed during the Snowmass process, will pose extreme computing challenges for detector simulation. Compared to present-day experiments, data volumes will grow by at least an order of magnitude. Additionally, detectors will incorporate novel technology to increase the precision of physics measurements, thus demanding more detail in geometry descriptions and accuracy in physics models. The number of events in `Geant4`-based simulation samples will therefore have to increase accordingly, and so will the fidelity of its physics modeling. During the LHC Run 2 for CMS and Atlas, `Geant4` used 40% of all computing resources [43], while for LHCb the corresponding number is ∼70% [44, 45]. For CMS, it is projected that only 14–20% will be available for simulation at the HL-LHC [46, 47].

In addition to high energy colliders, experiments of various sizes that search for light or weakly interacting particles rely on `Geant4` [34, 48, 49]. A wide range of other experiments face similar computational challenges to process petabytes of data, including the corresponding simulation of background and signal processes across a wide range of energy scales, from TeV muons to optical photons traversing meters of complex materials. The need to meet these challenges with substantially less personnel makes the development of common software even more important. Future neutrino, dark matter, and other similar experiments will obtain even larger data volumes and probe even more precise physics, increasing the computational challenges and the associated need for high-performing and well-supported software.

The increasing breadth and precision of next-generation HEP experiments will require computationally expensive improvements in the physics models used in `Geant4` [42]. The future of detector simulation software is therefore turning toward the use of GPUs, targeting, in particular, HPC facilities that are intended to provide a larger fraction of HEP computing for next-generation experiments [41]. Because detector simulation is naturally an HTC problem, nontrivial effort is required to adapt the necessary computations to use computer accelerators effectively. Two ongoing projects, AdePT [50] and Celeritas [51, 52], the latter led by US national laboratory personnel, have produced viable prototypes of high-performing GPU-native simulation engines. However, there is a significant burden in developing and maintaining coprocessor-friendly code, including portability to different GPUs platforms and, potentially, future non-GPU architectures. Another avenue to achieve faster simulation is the use of machine learning to replace or augment existing "classical" (rule-based) simulation engines [53]. Full replacement is commonly pursued using generative models such as generative adversarial networks (GANs), variational autoencoders (VAEs), or normalizing flows (NFs), although achieving an acceptable level of physics fidelity presents a significant challenge. Augmentation to improve lower-quality results, sometimes called refinement, can be applied to classical fast simulation engines or to generative models, using techniques similar to those above or regression-based approaches. The possibility also exists to use coprocessors more cost-effectively and efficiently by performing the ML inference as a service, avoiding the need for each CPU to be equipped with a GPU [54].

The above solutions, including GPU prototype transport engines and ML algorithms, are promising avenues for faster execution of detector simulation. However, it is unlikely that these will completely supplant `Geant4`, which provides broad support for a diverse set of use cases. Therefore, some percentage of general purpose von Neumann CPU-based computing will be needed in HEP for the decades to come. There is a strong consensus throughout the field that the decline in detector simulation investment, including the `Geant4` toolkit, must be reversed, with funding not just restored, but increased above historical levels.

4.3.4 Physics generators

The physics generator software landscape is complex and varied because it needs to provide solutions to different aspects of event generation: event (matrix element) calculation, hadronization and parton shower modeling, underlying event tuning, parton matching and merging, particle decays, cross section calculations, parton distribution functions, data formats, and analysis and reinterpretation. There are many software packages that address some of these needs, which often include plugins to perform specific calculations and provide ways for users to plug in their own custom models and computations. Physics generation is more or less computationally expensive, depending on the precision of the calculation. Overall, the percentage of grid computing time used for event generation at the CMS and ATLAS experiments is estimated to be 5–12%, with similar or even more substantial requirements expected for ALICE and LHCb [55]. Moving from LO to NLO and higher orders, or increasing the multiplicity with additional partons [56], typically causes a factorial increase in CPU usage for the same processes, while different processes may still have very different baseline computational requirements. The memory usage and multithreading abilities of different generator software are also highly variable and can lead to inefficiencies. Generator CPU usage is projected to increase to 8–20% in the HL-LHC era, when higher precision will frequently be required [46,47]. The generator usage at neutrino frontier experiments has not been measured and profiled as systematically, although we know that the computing budget is generally smaller compared to the energy frontier. However, the increasing precision of upcoming neutrino experiments such as LBNF/DUNE and HyperK is expected to require similar increases in experiment computing time devoted to event generation. Further future experiments will have different generator needs depending on their initial states.

Physics generators software faces challenges, especially when it comes to keeping up with the increasing demands for both physics precision and computing efficiency. The automated computation of NLO and higher order diagrams, introduces events with negative weights, which can substantially reduce the statistical power of the final result. There are also inefficiencies in phase space sampling, e.g., in slicing, biasing, or filtering, to change kinematic features, and in merging to avoid double-counting between matrix element generators and parton shower modelers. Further, use of generators by experiments may involve significant repetition of expensive calculations, especially to assess certain systematic uncertainties that cannot be represented as alternative event weights. Historically, there has not been a single obvious locus to coordinate common activities, even if MCNet (https://www.montecarlonet.org) and, more recently, HSF have provided useful forums, especially in the areas of training and computational efficiency, respectively. In the future, more emphasis should be placed on establishing and coordinating common activities. Projects to reduce the computational burden of event generation, for example by adapting to use GPUs, need a substantial increase in effort in order to be successful. An opportunity comes from the possibility to parallelize the matrix element calculations, which take up more than most of the computing time for complex LHC physics processes. Matrix element calculations are a perfect fit for CPU vectorization and hardware acceleration on GPUs. The use of ML for approximate matrix element calculations, including phase space integration and sampling as well as fully generative models is also very promising, but still in a relatively early stage of R&D. Additionally, there are efforts currently underway to explore the use of ML for parton shower modeling, hadronization, event (un)weighting, and tuning [57]. Some of the difficulties that generators face in computing are intrinsically tied to the nature of the calculations being performed, so fundamental research may be required to develop better methods. Overall, event generators are usually supported by small teams that frequently have little to no dedicated funding and cannot adequately plan for succession. As with detector simulation, it is vital to the entire field that funding is provided for permanent positions to support, improve, and expand these crucial components of HEP software. It has been suggested that a diverse and cross-cutting collaboration, similar to MCNet in Europe, could bring together the U.S. event generator community to share resources and ideas [57].

4.3.5 Continuum Field Theory Calculations

Continuum field theory calculations include both precision high order perturbative calculations and conformal bootstrap theoretical calculations. Precision is important to future experiments, where electroweak processes are moving from percent scale accuracy down to per-mille accuracy. This sets the goal for precision electroweak phenomenology on a range of processes. At the high luminosity LHC, even rare processes like Higgs production require theoretical control of cross sections at the 1% level [58]. Since the 2013 Snowmass exercise, the state-of-the-art has advanced dramatically and now next-to-next-to-next-to-leading order N^3LO QCD calculations for $2 \to 1$ processes and NNLO QCD calculation for $2 \to 3$ processes and $2 \to 2$ processes with internal masses are becoming state-of-the-art and reasonably fast on contemporary computing resources, while automation and more complex final states at NNLO and diboson production at N^3LO are goals for the Snowmass period [59].

The computational challenge is to perform Feynman loop integrals within perturbative quantum field theory, giving access to the scattering matrix and its analytic structures, often involving non-standard special mathematical functions. Numerical integration software is increasingly able to use GPUs. New semi-analytic methods for solving master integrals have been developed and reduce evaluation times to order of a minute per phase space point for two loop integrals. QCD corrections to scattering amplitudes have been fully automated at NLO using many public and private tools. A core computational bottleneck is in the handling of linear relations between Feynman integrals (integration by parts identities) to reduce many graphs to a limited set of master integrals. From a computational perspective the use of modular arithmetic in the calculation of integration by parts reduction is an interesting transformation of the computational requirement that may require radically different computing hardware solutions. These calculations require a significant amount of memory per core. The development of codes for challenging amplitude calculations in a HPC friendly way may have large memory demands and require run-times that are possibly well beyond available batch limits on a given cluster. Projected computational costs of different multi-loop calculations envisioned in the Snowmass period extend to as much as 10M CPU core hours in some cases [58]. Although there is some role for GPUs in numerical integration, they only match a modest part of the scientific requirement [58]. Large memory and runtime limitations imposed by typical HPC environments mean that bespoke computing nodes and queues are required to enable these calculations. Machine learning does not at this time play a large role, although some applications have been used in event generation.

The idea of the conformal bootstrap is to constrain and solve conformal field theories (CFTs) using physical consistency conditions like symmetry, unitarity, and causality. By relying on nonperturbative structures, bootstrap methods can work even in strongly-coupled systems where traditional perturbative techniques fail. From a computational perspective, the bootstrap methods suffer two key algorithmic challenges: the need to find faster optimization methods and efficient methods for exploring high-dimensional spaces of CFT data. Distributed high precision arithmetic which can be parallelized over many HPC nodes and hundreds of thousands of cores is required, leveraging new hardware like GPUs and FPGAs.

Both multi-loop perturbative calculations and numerical conformal bootstrap have a similar computer hardware requirement. They both have a current software reliance on CPU cores, and a large memory per core requirement. Perturbative calculations have a sizable barrier to the use of GPUs, while the conformal bootstrap approach, after significant software engineering, may be amenable to GPU or FPGA acceleration of high precision arithmetic.

4.3.6 Lattice QCD

Lattice gauge theory provides a systematically improvable numerical evaluation of the Euclidean Feynman-path integral for making first principle predictions of Quantum Field Theories. Worldwide lattice gauge theory efforts directly support numerous high-energy physics experiments by calculating properties of hadrons that are vital to interpretation of many experiments. These efforts make significant use of supercomputers and are critically dependent upon continued computing advances. Today, simulations of Lattice QCD provide precise model-free theoretical predictions of the hadronic processes underlying many key experimental measurements: for example determining the hadronic contributions to the anomalous magnetic moment of the muon (Muon g−2) [60], understanding of nucleon structure and parton physics, contribution of CP violating operators (in SM and BSM) to neutron electric dipole moment, the form factors for neutrino-nucleus interaction (critical to DUNE), quark-flavor physics, anomalies in the B sector (LHC, Belle II), in reconciling the CP violation observed in kaon experiments with the SM, and exploring rare kaon decays [61–63]. A critical review of important lattice QCD predictions that are considered mature with respect to control over all sources of errors is carried out by the Flavour Lattice Averaging Group [64] every two to three years to inform the larger community of progress and predictions.

Achieving the precision in lattice QCD calculations to satisfy the needs of the experiments requires simulations at finer lattice spacing and larger volumes, which needs further algorithmic research, novel computer hardware design beyond the exascale, improved software engineering, and attention to maintaining human resources [65]. Present algorithms display growing limitations as substantially greater ranges of energy scales are included in the problem, an algorithmic challenge called critical slowing down. The development of numerical algorithms is a significant intellectual activity that spans physics, mathematics, and computer science under investigation in the context of exascale computing, ML including tensor networks, and quantum computing.

The massive vector parallelism of lattice gauge theory is, in principle, amenable to GPU and possibly other acceleration. This imposes a significant additional programmer overhead and the need for the most commonly used packages to receive sufficient investment (GRID [66–68], MILC [69,70], CPS [71], Chroma [72] and QUDA [73]). For smaller projects, especially where rapid development and programmer productivity are at a premium, it is better and more cost effective in terms of human effort to maintain access to a range of CPU resources. USQCD institutional clusters at Brookhaven National Laboratory, Fermilab, and Jefferson Laboratory have been instrumental in supporting the significant number of smaller and experimental projects that would not achieve the return on investment to justify bespoke software development for multiple architectures.

4.4 Machine Learning

Multivariate analysis has a long history in HEP. Many of the discoveries made in the last decades were enabled, accelerated, or otherwise improved through the use of machine learning (ML) techniques. For example, ATLAS and CMS have published over 600 papers searching for new particles and the `TMVA` multivariate analysis package [74] is cited in over 10% of them. This does not include the analyses that use per-object ML-based classifiers (such as flavor tagging), which are likely a large fraction of all searches. Modern machine learning and deep learning in particular have the potential to significantly improve performance across the board. At the same time, these novel approaches have created opportunities to optimize research in qualitatively new ways. Additionally, cross-cutting developments have built bridges within the HEP community as well as with other areas of science and with industry. These facts have justified the inclusion of a dedicated ML topical group in this Snowmass process for the first time.

We have identified a number of areas that require dedicated resources in order for ML in HEP to flourish over the next years:

Dedicated HEP-ML Research While industry is driving many of the developments in machine learning, HEP has unique challenges that require dedicated solutions. For example, the level of precision we require and the use of simulation-data hybrid methods for inference call for HEP-specific research in the areas of uncertainty quantification (UQ), validation, and interpretability. Furthermore, HEP data have a complex structure that can benefit from physics-aware learning with custom ML architectures, learning strategies, and/or evaluation metrics. This structure includes non-trivial geometry/topology/enumeration (vector, set, list, image, tree, graph, point cloud, etc.) as well as invariance/covariance under various symmetry groups. One way to engage the broader ML community in these research topics is with the development of well-curated public benchmark datasets.

There are also a number of HEP research areas where machine learning has traditionally not played a role, but where modern machine learning has the potential to be transformative. One such area is 'particle theory'[2], including simulation and lattice gauge theory. A class of ML methods called generative models are able to emulate complex probability densities in high dimensions, which can be used to augment or accelerate various steps of the HEP simulation chain and also may solve key challenges in lattice gauge theory. The research area called *simulation-based inference* (also sometimes synonymous with *likelihood-free inference*) is the optimal combination of simulations with ML and may enable analyses that are not possible with classical methods. In particular, such tools allow for exploring the data and model parameter spaces in high dimensions moving from a multivariate approach to *hypervariate* analysis.

The opposite extreme is *anomaly detection* and other *label-free* learning strategies where ML may be used to reduce the reliance on specific HEP models. Such tools provide an orthogonal approach to traditional analyses and may be essential for broadening the HEP search program for new physics. Most HEP analyses are constructed with narrow hypothesis and anomaly detection may be a complementary tool for exploratory analysis. More generally, there is a spectrum of model dependence and ML methods can be used across this continuum and for both achieving signal sensitivity as well as estimating Standard Model backgrounds.

Another significant growth area for ML and HEP is instrumentation. ML methods can be used for all aspects of detector research, including experimental design, quality assurance/control, and calibration. A key insight from dedicated HEP-ML research is to cast HEP problems as ML problems and then use the most effective optimization strategies available. For example, gradient descent is one of the most efficient optimization procedures and experimental design can be optimized in this way if detector simulations are made differentiable (through *differentiable programming*) or if a differentiable model (called a *surrogate model*) such as neural network is trained to emulate a detector. There is a direct connection between how an ML problem is set up and the physics outcome of the optimization. Using out-of-the-box approaches may lead to undesirable properties such as prior dependence, bias, etc.

Additionally, ML may be useful for control at experimental facilities such as particle accelerators. Ultra low-latency inference is relevant for facilities and experiments and this is another area where HEP can contribute approaches that may be useful more generally.

Many of the topics mentioned above are inherently interdisciplinary and so funding structures that are inherently cross-cutting are essential for success. Recent interdisciplinary institutes from DOE and NSF that involve HEP are excellent examples of cross-cutting structures.

[2]Quotes used here because ML method research blurs the lines between 'theory' and 'experiment' in a productive way that draws on insights from both communities.

Software and Hardware Needs For many years, `TMVA` was the most common ML tool in HEP. Now, there is a more diverse ecosystem with many people relying on industry standards such as `SciPy` [24], `TensorFlow` [75], and `PyTorch` [76]. All of these tools are open source and we should support HEP software specialists to directly contribute to these projects to ensure that HEP needs are met and to give back to the broader community. Incentives could be created for code sharing and reproducibility through expectations from funding sources.

In addition to a heterogeneous software ecosystem for ML, there is also a diverse set of hardware tools available for modern machine learning. Graphical Processing Units (GPUs) are essential for enabling a reasonable development cycle. While GPU resources are available from many computing centers, it is often invaluable to to have a dedicated GPU system for prototyping. Research grants funding ML could be even more effective if they also carried a small hardware component. For larger tests and for deployment, high performance computing centers are essential. This requires allocation systems to be amenable to R&D and for computing systems to be compatible with standard software packages so that the typical HEP researcher does not need GPU programming experience.

There is significant R&D in industry for developing even more advanced hardware accelerators for machine learning training and inference. The HEP community should stay connected with developments in these areas through direct connection to industry and through computing centers. Additionally, the HEP community may have more stringent latency and radiation tolerance requirements for certain inference tasks (trigger systems, operations in space, etc.) that may require custom solutions. Development in this area will require collaboration with instrumentalists within and outside of the HEP community. Lastly, training and deployment of machine learning algorithms may benefit from cloud and other on demand services, which may reduce the need for custom hardware to be on premises. The exact portfolio of HEP-funded hardware investments versus using community resources should be optimized.

Training and Personnel The ubiquity of ML for all areas of HEP science means that these tools should be part of the standard training program. This could take many forms, including graduate school courses on ML as well as summer schools. There are a growing number of examples for both of these topics and the community could benefit from sharing ideas/experiences in order to refine curricula for the future. HEP could consider joining/supporting or otherwise creating training materials similar to what the APS Group on Data Science is organizing through its Data Science Education Community of Practice (DSECOP).

In addition to broad training, we also need to have a training path for researchers who want to develop new methods at the intersection of HEP and ML. To be best prepared for a career in this area, it is essential that researchers have a solid statistical foundation in addition to acquiring practical experience with applications. Some programs are starting to develop along these lines, such as the PhD in Physics, Statistics, and Data Science at MIT and the Designated Emphasis in Computational and Data Science and Engineering at UC Berkeley. However, training these researchers is not sufficient; we must also provide a career path for them within HEP. ML is a catalyst for cross-cutting research and HEP ML specialists could help connect traditionally isolated areas of HEP. It is imperative that we take a broad perspective to recruit and retain a diverse cross-section of scientists. Capitalizing on industry expertise with cross-disciplinary collaboration will require community assessments of the ethics of such arrangements and new devices for external collaboration with HEP experiments.

4.5 Storage and processing resource access

The computing landscape has changed a great deal since the 2013 Snowmass Planning Exercise. Some of the changes include dramatic changes in processors and widespread availability of heterogeneous nodes. Also, there has been increased reliance on national supercomputer centers for the experimental program, and cloud computing has developed significantly. We are just at the dawn of the Exascale era. In the US, these computers all feature graphical processing units (GPUs) and generally have robust storage systems, but they are not ideally suited for much of the HEP workload. Distributed computing in which multiple and far-flung computers and storage units are employed is very much the norm in HEP computing, so networking considerations are also essential for this topical group. The Storage and Processing Resource Access topical group has focused its attention on the implications of these developments on research and development challenges that must be addressed in the next decade. The group did not attempt to assess the required capacity of either computers or storage across the spectrum of HEP activities in that period.

This topical group divided its efforts into six areas: storage; processing; edge services; AI/ML hardware; analysis facilities; and networking. There were some common issues that we will focus on before looking at specific areas. High energy experiments are often international efforts. Their computing resources can be globally distributed with different nations providing compute and storage resources. Thus, there is global flow of data among these resources. CPU speeds have not been increasing for many years and increased processing capability comes from parallelism with multicore, wide vector or massively multithreaded hardware, with some computers applying all three. In addition, processors designed for machine learning, FPGAs, and tensor processing units add to the heterogeneity of the current computing environment. This leads to both an opportunity to increase the cost effectiveness of computing and the research and development challenge of making use of this diversity.

Four overarching themes, each of which appears in several sections of the report, have emerged:

1. **Efficiently exploit specialized compute architectures and systems**
2. **Invest in portable and reproducible software and computing solutions to allow exploitation of diverse facilities**
3. **Embrace disaggregation of systems and facilities**
4. **Extend common interfaces to diverse facilities**

Exploiting specialized architectures will require the allocation of dedicated facilities to specific processing steps in the HEP workflows, in particular for "analysis facilities" (discussed in topical group report Secs. 4.2 [Processing] and 4.5 [Analysis Facilities]); designing effective benchmarks to exploit AI/ML hardware (report Sec. 4.3 [AI/ML Hardware]); improved network visibility and interaction (report Sec. 4.7 [Networking]); and enhancements to I/O libraries such as lossy compression and custom delivery of data (report Sec. 4.4 [Storage]).

The need for investment in portable software libraries, abstractions and programming models is particularly ubiquitous and detailed in Secs. 4.2–6. The last two sections discuss the need for software frameworks to enable reproducible HEP workflows.

Large HEP experiments cannot provide a single computing center for all their needs so must embrace the disaggregation. This will require research on efficient distribution of workflows on heterogeneous facilities, including software abstraction to integrate accelerators, orchestration of network resources, exploiting computational storage and rack-level memory pools, and is detailed in Secs. 4.3, 4.4 and 4.7.

The fourth theme of extending common interfaces to diverse facilities is essential to enable use of those facilities by the many scientists who might make use of them. It is also important for multiple experiments to embrace these interfaces to reduce development costs. We also must not lose sight of the global context of our computing tasks. The OSG Consortium and Worldwide LHC Computing Grid (WLCG) represent a successful style of distributed computing. HEP must continue to encourage edge-service platforms on dedicated facilities as well as Cloud and HPC, and develop portable edge-services that are re-usable by other HEP projects and exploit commonality within HEP and other sciences (Sec. 4.6). These interfaces will also need to extend into all aspects of HEP workflows including data management and optimising data movement (Secs. 4.2, 4.4 and 4.7); as well as the deployment of compute resources for analysis facilities (Sec. 4.5).

It will be challenging to train and retain a workforce that can deal with these research and development challenges. For instance, there is currently no single programming model to deal with offloading tasks to computational accelerators such as GPUs and FPGAs. Each of the major GPU vendors for upcoming exascale computers has its own approach. For NVIDIA, it is `CUDA`; for AMD, `HIP`, and for Intel, `DPC++` or `Sycl`. In addition, OpenMP is developing better offload capabilities, and there is a movement to incorporate parallelism within standard languages such as `C++`. The DOE is investing in the `Alpaka`, `Kokkos`, and `Raja` approaches to portability to simplify the task of writing code that a compiler can optimize for different architectures. Expertise in dealing with security issues required for distributed computing is also rare.

In regards to processing, there are four recommendations.

- HPC facilities should revisit their resource access policies to allow more flexible allocations and job executions. This, coupled with new authentication and authorization models, will allow more HEP projects to benefit from the large computing facilities.
- Investment in software development effort is key to maximize the efficient utilization of diverse processing resources. In particular, research and development of portable software solutions is critical for a sustainable software ecosystem in light of the evolving and increasingly diverse hardware architectures.
- Research is needed to determine the tradeoff between dedicated HEP computing facilities and general-access computing facilities such as the HPC center, Grid and Cloud resources.
- Infrastructure development will be needed to support better data management frameworks across different types of facilities.

Hardware for AI/ML is quite diverse and changing rapidly. Although there are many machine learning benchmark suites, a suite focused on HEP applications should be developed and used on current and new hardware in order to select the best hardware for our needs. AI/ML hardware can considered to be either directly connected or via a network denoted "as a service."

Storage requirements for LHC experiments CMS and ATLAS are vast and present a major challenge given current and projected hardware budgets. We anticipate that tape will continue as the archival medium. Spinning and solid state disks will continue to co-exist, though the cost advantage for spinning disks continues to favor them for the bulk of the required capacity. Research is underway on new data formats that are smaller or more efficient for modern processors. `HDF5` may be useful at HPC centers with parallel file systems. I/O frameworks will be needed to evaluate data-format performance (building on existing work conducted under HEP-CCE for example [20]). Work is needed on both lossless and lossy data compression to reduce storage costs. The separation of storage and processing presents a challenge to the network and one mitigation is to provide "computational storage," in which some compute capability is embedded within the storage. There are a number of technologies that need to be tracked as detailed in Sec. 4 of the topical group report.

Infrastructure and services will be needed that provide integrated data, software and computational resources to execute one or more elements of an analysis workflow. For example, the HL-LHC will present a daunting challenge to physics analysis teams. To prepare for the that challenge IRIS-HEP is organizing an "Analysis Grand Challenge" to test new concepts for and prototypes of analysis facilities. The Analysis Grand Challenge workflow defines an analysis benchmark that could be easily re-implemented and executed on any generic Analysis Facility and is designed to help to showcase to physicists how to use an existing analysis facility at scale for their analysis. Several contributed papers [20] discuss new concepts and features to be investigated. Modern analysis tools such as machine learning, and fitting as a service run well on high performance computers and should be integrated with analysis facilities. Security in distributed computing environments is a critical issue and work on federated identification needs to continue. For example, NERSC is currently extending its authentication to allow users to login via credentials from their home institution. This is enabled for most national laboratories. Section 5 of the topical group report provides many more details.

Edge services operate at the interface between a data center and the wide area network, separated from the data center's core services. This includes middleware that facilitates user access between the data center and external systems (e.g., storage, databases, workflow managers). These services may be managed externally in partnership with the data center and federated across multiple data centers. Containers can provide executable code for services in a portable manner, as they contain all the needed software and libraries. Kubernetes is one example of system to create and distribute containers with very widespread industry usage, that will require further development to fully adopt into HEP workflows and resources. We have already mentioned security and federated identity services as requiring additional R&D. We expect that HPC centers and HEP experimenters will make increasing use of edge services, so it will be necessary to follow technical developments in this area.

In a world of distributed storage and computing, the network is essential for getting work done. Particle physics network traffic is expected to grow by a factor of ten by the end of this decade. (For details, please see the recent ESNet HEP Network Requirements Review.) Four interrelated networking issues have been identified: network interaction optimization; resource orchestration and automation; network and traffic visibility; and data movement optimization. The first issue ensures that applications efficiently put packets on the network. The second issue is one of coordinating schedule activities of storage systems, compute infrastructure and the network in order to reduce delays in a workflow. The third and fourth capabilities are necessary for efficient orchestration since there must be a way to estimate the time to move data and the best way to route it. These four areas must be worked on together. The technology landscape changes quickly over time, and well-organized collaborations staffed with knowledgeable experts can make effective use of current and future technologies, whatever they may be. It is critical that particle physics make long-term investments in collaborations between scientists and technologists so that cutting-edge networking technologies can be effectively used by us. These collaborations must combine research, prototyping and production implementation, as this is the only way that components and technologies can be effectively integrated into the scientific enterprise as effective capabilities. Prototypes offer powerful means of demonstrating new technologies and capabilities, allowing evaluation of cost, complexity, effort and maintainability. In all the identified areas, we suggest that there be work plans that clearly identify the steps and decision points from prototyping to production. Each of the four areas is detailed in Sec. 7 of the topical group report.

4.6 End user analysis

End user analysis infrastructure is of fundamental importance to guarantee the fast turnaround in the process of running analysis code on full data sets with the frequency needed for timely delivery of physics results to be presented in conferences and published in scientific journals. Fast, easy, and user-friendly access to analysis level data formats is a primary premise in the collaborative process that allows analysis teams to assemble all elements of a physics measurement and iterate efficiently and quickly to produce a final result and go through internal and external peer review.

No analysis software functions entirely on its own, but in the context of the input data it consumes, the output data it produces, the other software it depends on, and the way it is configured or embedded in other code. We therefore talk about a "software ecosystem." Packages in an ecosystem typically have common data interchange formats and similar programming language interfaces. There are two major ecosystems relevant to data analysis in HEP, based on ROOT and Python. The ROOT suite is a set of libraries that covers a broad range of needs, including I/O, event loop execution, histogramming, statistical analysis, and visualization. It is hosted by CERN with a leading contribution from the US to I/O. The libraries are written in `C++`, although the Python bindings (`PyROOT`) are well supported and expose essentially the full API. There is also `UpROOT` (see also `Scikit-HEP`) which is pure Python and does not require compiling ROOT. Bindings for the R language are also currently supported. The tightly-bound nature of ROOT means that using alternative software for any particular functionality can be very difficult. Of particular interest is the planned evolution of the TTree into the n-tuple and nested tuple (`RNTuple`) columnar data storage. This development will speed up analysis by improving the mapping to vectorized and parallel hardware and provide better memory control. Python is a loose term for a set of tools, with Python as the primary language interface, introduced with the primary goal of enabling the use of software developed outside of HEP, including for machine learning. This ecosystem is still in development and has no single governance team. It tends to emphasize independent packages for different aspects of the analysis pipeline. Development teams in this ecosystem within HEP are typically small and feature junior personnel. While there are a number of HEP developments within `Scikit-HEP`, it would be interesting to consider to what extent the HEP community can and should contribute to the broader scientific Python ecosystem.

Users interact with software libraries and packages through programming languages. These can be separated into general-purpose languages (GPLs) which can be used for any task, and domain-specific languages (DSLs) which provide a restricted set of higher-level primitives which simplify certain operations. The two most commonly-used general-purpose languages in HEP are `C++` and Python. Examples of domain-specific languages are the `TCut` syntax used for applying selections and constructing new variables in ROOT, and the `kumac` language used to control the old FORTRAN-based `PAW` suite. DSLs have been historically easier to master than GPLs due to the limited range of constructs available. DSLs also have the advantage of providing high-level primitives which facilitate parallelization and acceleration. Python came to be adopted by users as a convenient language and its simultaneous adoption as the standard language in machine learning has driven massive bottom-up adoption of the language. However, since it can be slower than `C++` for some tasks, there is interest in exploring languages that can combine its expressiveness and ease-of-use with compilation to machine code; the most commonly-explored option is `Julia`. There are also emerging paradigms within Python (and `Julia`) that use differentiable and probabilistic programming for optimal analysis.

Visualizations are increasingly being done via web browsers such as `Jupyter` notebooks or `JSROOT`, which follow common standards to offload rendering and interaction to the browser, resulting in a more uniform experience across platforms and reduced external dependencies. This is the baseline for future ROOT graphics. As the dominant language in that environment is JavaScript, expertise will need to be maintained at some level. End-user analysis relies critically on visualization to give feedback to the physicist. Plots allow the user to quickly understand characteristics of the data but also to debug code and workflow problems.

Although event displays are not typically used as part of an analysis workflow, they are still of interest to end users, and the same issues apply. Work is being done on experiment-agnostic event displays that render in browsers using JavaScript.

Data formats target different processing and analysis needs. Event data is encoded in a fixed but complex schema, describing individual events. Histograms summarize features extracted from event data. There are forms of summary data that cannot reasonably be expressed via histograms and they are presented in a tabular format. The configuration for running some software may be stored in a human-readable and -editable format, or in a binary format. File formats can describe both the overall container for data and the specific types of objects that can be stored. ROOT separates these fairly strictly, in that the ROOT file format can store essentially any `C++` object, and ROOT objects can be serialized to formats other than ROOT files (such as JSON or XML). ROOT provides a number of pre-defined data objects, such as tables (known as TTrees) and histograms, and multiple objects can be present in the same file.

Once analysis code is written, it must be run on data. An analysis pipeline may involve multiple stages of data reduction and different codes, executing on very different platforms. Because the rapidity with which analysis workflows can complete is paramount, data processing architectures which are well-suited to managed production workflows may not match well on to analysis tasks. Users need to be able to scale code execution from a few events (for testing) to an experiment's full dataset. The former requires interactive response, while the latter may require distributed execution. Consequently, solutions that smoothly scale from small-scale interactive tests to full-data processing are desirable. Interactive use historically has occurred via terminal sessions, while distributed execution has occurred on the grid, with complex issues of data locality and access, bookkeeping, job brokering, fair access, arising. Particle physics problems are usually *high-throughput*, not *high-performance*, problems. They consist of a very large number of fairly lightweight computations which are essentially independent of each other, and so do not require computing resources to appear as a single, very powerful image (as on a traditional supercomputer). Traditional tightly-coupled supercomputer execution environments are therefore not typically needed for HEP analysis applications and in fact may be detrimental as they do not exploit the fine granularity of HEP problems. However, the increasing exploitation of coprocessors and accelerators (such as GPUs) in HEP code requires libraries that couple CPU and GPU execution on a single node. One line of research explores analysis facilities which would provide users with alternate mechanisms to access computing resources and enable new programming paradigms. `Coffea-Casa` is a prototype analysis facility, which provides services for "low latency columnar analysis", enabling rapid processing of data in a column-wise fashion. This provides an interactive experience and quick "initial results" while scaling to the full size of datasets. These services, based on the `Dask` parallelism library and `Jupyter` notebooks, aim to dramatically lower the time for analysis and provide an easily scalable and user-friendly computational environment that will simplify and accelerate the delivery of particle physics measurements.

In order to serve the long-term end-analysis needs of the community in a sustainable way, it is important to take action on a number of recommendations. Firstly, **software work (especially with cross-experiment application) should receive stronger consideration for funding.** More cross-experiment/frontier computing physicist positions could be created. Funding agencies and frontiers need to work together to identify viable long-term funding patterns for this work.

More specifically:

- **Develop both ROOT-based and Python-based analysis ecosystems.** The friendly competition between the two has already resulted in significant improvements for users. Maintaining interoperability between the two, e.g., data formats, should be a requirement.

  - Critical elements of the ROOT evolution plans include the development of improved columnar data formats (evolution of TTree to the more-optimized RNtuple) and the multiple I/O implementations.
  - Analysis facilities for low latency columnar analysis in the context of the Python ecosystem will be essential for future experiments.

- Effort should be put into **developing user-friendly data provenance and metadata storage systems** that can be easily integrated into typical analysis tasks.

- **Scalable analysis models** should be developed to allow users to perform interactive tests and run over large datasets using a single interface.

- **Pipelines compatible with long-term preservation** should be built into the structure of analysis systems as the default.

- **Collaborative software** is an important element of the analysis software stack of an experiment, and includes documentation, messaging between users, discussion forums, software version control, bug tracking, and document workflow management. Host laboratories should provide a full stack of these services to their experiments, large and small.

- **Documentation and training** must be produced for analysis software understood as an ecosystem, not as a disconnected set of packages.

4.7 Quantum computing

Quantum computers (QCs) exploit quantum effects such as interference and entanglement to perform calculations. These devices are like classical computers in that they can be (re)programmed to perform many different calculations. However, current QCs are relatively small and noise is a significant challenge. This has naturally divided research into R&D on near-term devices and R&D for future *fault tolerant* computers. The setup of near term QCs is similar to a small HEP experiment at a user facility in terms of the steps to initiate and process a measurement. Similar to other HEP experiments, we are striving to discover new insight with these experiments. The research and experience with near term computers may also inform R&D for the fault tolerant era. While quantum computing is closely related to other areas of quantum information science (theory, sensing, and networking), we focus solely on the use of reprogrammable quantum hardware ('quantum computers') in this section. Rapid progress in hardware and software over the last years has enabled a rapidly growing research area of software for QCs. Open source tools exist for writing algorithms to manipulate quantum computers and these algorithms can be deployed on quantum hardware similarly to a classical batch system. These significant advances have motivated the dedicated topical group on QC for HEP.

Even relatively small QCs can outperform classical computers for certain questions. This is because QCs can represent an exponentially large Hilbert space with polynomially many qubits. However, not all exponentially hard problems can be efficiently solved on a quantum computer. It is also possible that fault tolerance will be required for going beyond classical computers. Nonetheless, it is necessary for HEP scientists to participate in near-term computing efforts (called the NISQ era [77]) in order to develop motivational examples, to grow a QC for HEP workforce, and to build critical infrastructure for the future. While the timescales are not clear, it is possible that fault tolerance will be achieved for the next Snowmass process in about a decade. It is clear that QC technology will continue to improve at a rapid pace over the next years.

A number of benchmark problems have emerged which have focused the QC for HEP community and which are particularly promising. These include lattice gauge theory, event generation, and data analysis. While classical lattice gauge theory is a well-established tool to solve a number of questions that cannot be addressed with perturbation theory, there are significant limitations (the *sign problem*) for answering all non-perturbative questions [78]. Lattice gauge theory on a quantum computer may be able to solve these challenges. Hybrid methods that combine classical and quantum computations are also promising, especially with near-term devices. Monte Carlo event generators are also able to achieve excellent precision for many observable, but there are some regimes where quantum effects are large and hard to model with classical methods. The potential for classical data analysis with quantum computers is less clear because of the significant overhead to transform the data itself into a quantum representation. Nonetheless, there are cases where the best quantum algorithms are at least polynomially faster than their corresponding classical counterpart and other cases still where early empirical results are promising. Gains may be larger for data from quantum sensors that are inherently quantum. Continued investment in identifying benchmark problems is crucial, also to engage the non-HEP QC community.

A significant difference between quantum and classical computers is that there is no consensus on the hardware underlying quantum computations. Candidate technologies include superconducting qubits, trapped ions, and photonic systems. Some systems are publicly available and others require specific agreements with particular laboratories or companies. Access to quantum computers is a challenge for researchers and this barrier could be eliminated with coordination across the HEP program. There are also exciting opportunities for co-design whereby quantum computers could be constructed that are tailored for HEP applications. This important research area will require collaboration between HEP QC experts and QC hardware researchers (likely not in HEP). More generally, the connection between QC and HEP is not one way as the HEP community has expertise that could benefit QC generally. Taking advantage of partnerships between HEP and non-HEP entities (including national QIS centers) is an effective strategy for mutually beneficial research.

There are also a diverse set of software packages for specifying quantum gate sets and for compiling them to particular quantum devices. It may be beneficial for HEP to directly contribute to these packages to ensure that the evolving HEP needs are met in addition to providing a service to the broader community. Additionally or alternatively, it may be beneficial to create a community-wide codebase for HEP applications similar to `Qiskit Nature`.

As with many areas of software and computing, researchers with QC experience are in high demand. A growing number of Computer Science and Physics Departments are offering courses in QC, and these could be a component of the training path for a researcher at the intersection of HEP and QC. It is also vital that we forge career paths for these researchers, who often do not neatly fit into one of the existing frontiers. There is also an opportunity to build connections with industry, both for the science and for the career development of junior researchers.

There is also a strong synergy between QIS for HEP and QIS more generally. For example, many HEP scientists are members and leaders of the National QIS Research Centers and one of the centers (Superconducting Quantum Materials and Systems Center (SQMS)) is hosted at Fermilab. SQMS is leveraging decades of investment in superconducting technology in HEP to understand the physics of decoherence, and to build a quantum information processing platform based on superconducting radio-frequency (SRF) cavities. These processors may be particularly well suited to quantum simulation problems of interest inside and outside of HEP.

4.8 Reinterpretation and long-term preservation

The topical group devoted to Reinterpretation of Long-Term Preservation of Data and Code has considered what needs to be done to achieve these goals and the barriers to achieving them. In addition, it is argued that a facility should be set up to preserve data from Cosmic Frontier observations and simulations. This is just one example of the need for facilities for long-term data preservation, as discussed below.

Preserving data, simulations, analyses and the codes needed to do the analyses is a practice that can increase scientific output from the investments made in the original inquiry. Most scientists see that this is a benefit[3] to the wider community and, in principle, support this activity. However, to actually plan for and carry out such preservation requires resources and effort from scientists who many not have a strong incentive to do this work. The large, long-running experiments such a those at the LHC are in a better position to plan for long-term preservation than the smaller experiments. This is due to CERN support for data preservation and the fact that larger experiments tend to have more personnel devoted to S&C.

We recommend:

1. Ensuring that all running and in-preparation experiments have a strategy and resources for the long term preservation of data and analysis capabilities, extending beyond the lifetime of the experiment.
2. Investing in shared cyberinfrastructure to preserve these data and support a comprehensive analysis from various experiments and surveys—both active and completed—in order to realize their full scientific impact. The infrastructure should support the requisite theoretical inputs and computational requirements for analysis as well as metadata and APIs to track provenance and incentivize participation.
3. As mentioned above, as a specific example, there should be a data archive center to preserve Cosmic Frontier datasets and simulations, and facilitate their joint analysis across different computing centers.

We note that preservation needs are not restricted to experimental data and analyses. As an example, for many years, the lattice QCD community has had a tradition of sharing the expensive-to-produce gauge configurations that can be used for many physics analyses. NERSC hosts the Gauge Connection which is one facility for such sharing. The Gauge Connection has been described as their first web portal. Another effort started 20 years ago is the International Lattice Data Grid. However, these efforts are restricted to one type of data. Several groups have also made their simulation codes available, and there has been SciDAC funding to support community software that has been widely used.

Ideally, publicly released data should follow the data management principles of being Findable, Accessible, Interoperable, and Reuseable (FAIR) as described in Ref. [79]. Achieving this goal requires attention and resources throughout the end-to-end lifecycle of data generation, processing, analysis, preservation, and distribution. Reference [80] defines important concepts such as data, derived data, and analysis data products, which distinguish between the "raw" data coming from an experiment or simulation, to data reduced in some form, such as particle momenta and identities, to further products of analysis such a summary plots, etc. Data preservation is the procedures, practices, and standards of ensuring the long-term (i.e., decades beyond the end of an experiment) preservation, accessibility, and usability of data and derived data from experiments. Data analysis preservation is similar but its goal is to be able to repeat the analysis from the preserved data and reproduce the analysis data products. Two addition concepts are reinterpretation, i.e., any type of new, alternative or updated interpretation of an experimental analysis or result, including the combination in, e.g., global fits or global averages, recasting, which is reproducing the

[3] Although there is some disagreement about when and how data products and software should be made public.

analysis logic in a simulation, considering a different physical process with a different phase space distribution, which might have different efficiencies and acceptances than the originally hypothesised model.

Data preservation requires the long term curation, storage and distribution of the three data types defined above. CERN's Open Data Portal provides the infrastructure and services for CERN experiments, but there is no equivalent (in the US) for smaller experiments or theoretical data. For astronomical data, NSF and NASA provide several archival storage facilities, but DOE does not provide such infrastructure for DOE-funded Cosmic Frontier experiments. Coordination with national supercomputing centers would be welcome.

Preservation of analysis data presents its own challenges as there may be many formats. HEPData, run by Durham University and CERN contains data from nearly 10,000 publications, with over 100,000 tables of data. CERN provides the Zenodo site that is capable of sharing larger data sets and serves a wider community than high energy physics. With such infrastructure, the challenge is to get scientists to routinely archive their data as part of the publication process.

Preserving analysis software and logic present their own challenges; however, services such a GitHub, Bitbucket, and GitLab help to make it easier to distribute open source analysis code. Containerization can help to mitigate the dangers of operating systems or libraries changing in such a way that the code no longer works as it should. Machine learning models create a challenge in that the underlying software and the format of its model may change in an incompatible way. On the other hand, Jupyter notebooks are becoming very popular and their nonproprietary nature and ability to combine text, graphics, and code help to preserve the analysis logic. In addition. onnx provides an open standard for machine learning interoperability.

4.9 Personnel and Training

Two critical topics that emerged for all of the topical groups are (i) educating researchers to apply and develop advanced software and computing skills and (ii) ensuring there is a career trajectory inside HEP for computational researchers. The first topic is of great interest to other Frontiers, and also considered by the Community Engagement Frontier (CEF). The CEF also has a topical group on Career Pipeline and Development.

The current standard for S&C training is project-specific on-the-job training. These training activities can be very effective, especially with formalized curricula and documentation. However, these activities are often inaccessible beyond a particular experiment or other organization and due to limited person-power, these events often do not cover as deep or as broad as is needed to be maximally effective with S&C. These challenges can be solved with common training activities with persistent and accessible documentation. Some aspects of S&C training are not HEP-specific and we can turn to general computing and data science training materials (some of which have been led by HEP researchers). One example of this where HEP researchers have engaged larger efforts is through the The Carpentries. Other aspects of S&C are HEP specific and are best taught in the HEP context. In these instances, it is essential that we prepare training activities and widely-available documentation. A success story in this area related to Snowmass is the recent DOE funding opportunity *Traineeship in Computational High Energy Physics* (DE-FOA-0002743), which cites as motivation the 2013 Snowmass Computational Frontier report, in particular the one on Software Development, Personnel, and Training [15]. A number of other training programs have been hosted by DOE- and NSF-funded initiatives as well as by the HSF and other organizations.

Career trajectories in HEP S&C can take a number of forms. Early exposure to S&C topics can occur in undergraduate curricula. We strongly support DOE and NSF fellowships for graduate students who want to specialize in or have a major focus on S&C topics. Beyond graduate school, paths should exist for physicists who are experts in S&C as for physicists who dedicate their career to S&C as a research software engineer (RSE) or equivalent. In both cases, paths towards positions with long-term stability are essential.

4.10 Diversity and Climate within Computing in HEP

The percentage of Underrepresented Minorities (URMs) obtaining a Ph.D. in physics in the US is $< 5\%$ (Hispanics) and $< 2\%$ (Blacks), while the percentage of women is about 20% [81]. In computer science the situation is worse for Hispanics and Blacks, with approximately 1.5% of Ph.D. degrees earned by the former, 1% by the latter, while the percentage for women is about the same in computing and physics [82]. Representation of Hispanics and Blacks in both physics and computing stand in stark contrast with their numbers as a fraction of the US population, 19% and 14%, respectively. While gender and race disparities in physics and computing often receive the most attention, identity is multifaceted and individuals face adversity in the field based on their sexual orientation, religion, disabilities, immigration status, country of origin, and more. Interestingly, the situation was not always so dire for women in the case of computer science. In 1970, the percentage of women majoring in computer science was 12%, increasing dramatically to a 37% by the mid eighties, only to plummet and flatten out to a 17% by 2010 [83, 84]. Conversely, 7% of the Ph.D.s in physics were awarded to women in 1970, increasing linearly to eventually flatten to a 20% in the early 2000's [83]. There are several compounding factors that contribute to persistent diversity gaps in computer science including stereotype threat, implicit and explicit bias in higher education and society at large, isolation and lack of community, and more, as discussed in Refs. [84–86]. As compared to the overall participation within HEP, the participation of women in HEP S&C activities may be even lower. This would not be surprising, given that the prevailing culture within computing in HEP mirrors that of the computing community within society at large, creating climate-related barriers that undermine gender and race equality.

Another challenge the S&C community faces is related to the lack of recognition of the physics content of computing work within HEP, unlike the case of contributions to instrumentation, which are better rewarded career-wise. As the intersection of two highly specialized topics, there is an especially high level of knowledge and skills required to contribute successfully to computing in HEP. To get to this level, individuals usually must seek expertise outside of traditional HEP education and training, which typically does not cover computing topics in detail. This poses a discouraging burden, especially for those without connections to such expertise or without the resources to take on such additional work. It also creates in the physicist the perception that computing in HEP is an uphill and separate career path with different career success metrics and requiring a different set of skills. All these elements compound to create barriers which discourage participation, making recruitment and retention challenging among young physicists who are building their expertise on the computing aspects of HEP. Substantially expanded support for S&C training and for software development as a viable career in the HEP ecosystem would alleviate this burden. Support for strong recruitment efforts and dedicated mentoring programs would help increase and nurture the talent pool. A larger and healthier HEP computing community can be more welcoming and accessible to participants from all backgrounds.

As a first step, the US HEP S&C community should establish a study group to explore the challenges in the area of diversity, inclusion and climate that are particular to the computing sub-field within HEP. This group would be charged with the task to identify these challenges and produce recommendations to address

them. Any effort to characterize and address diversity and inclusion issues in HEP and computing must be multifaceted and intersectional.

4.11 Recommendations

Before expanding on the recommendations from the Executive Summary, we briefly revisit some important aspects of the Computational Frontier. The Snowmass process is mostly about the long-term, post 2035 period, with next- (or in some cases, next-to-next-) generation projects across frontiers. However, the near-term program, especially from the point of view of S&C, before 2035 is not completely determined, and we must make a strong case for it. We have focused on the upcoming 10-15 years, where we need to secure funding to bridge the resource gap of near-future programs and to account for the rapidly evolving technologies that make predictions beyond 2035 inaccurate. Despite this focus, we must also be cognizant of the near-term program required to address the needs of feasibility studies and R&D for future facilities. To complicate matters, computing technology and software paradigms change on a much faster scale than the life of particle physics experiments. Additionally, many S&C efforts are neither funded nor managed as projects, unlike facilities and experimental devices.

One of the purposes of the Snowmass reports is to inform the Particle Physics Project Prioritization Panel (P5). In the 2014 report [87], S&C topics were listed in recommendation 29 (out of 29):

> *Strengthen the global cooperation among laboratories and universities to address computing and scientific software needs, and provide efficient training in next-generation hardware and data-science software relevant to particle physics. Investigate models for the development and maintenance of major software within and across research areas, including long-term data and software preservation.*

The 2014 P5 report also has two paragraphs about S&C in the context of enabling the HEP science drivers. These paragraphs note that HEP played a leading role in high-throughput distributed/grid computing, online data processing, high performance computing and networking, large-scale storage, and the world wide web. We have successfully managed software development and operations on a global scale and computing in HEP continues to evolve based on needs and opportunities. Noted at the time were a variety of areas including (i) high performance computing and novel algorithms for realistic beams, (ii) the volume and complexity of physics data from LHC experiments stressing computing infrastructure and expertise (iii), cosmology programs extending data needs as vast new surveys and high-throughput instruments were coming online, and (iv) theory computations increasing in importance as higher fidelity modeling was required.

In 2022, S&C continues to be an enabler of the HEP science drivers. Computing is essential to all experiments and many theoretical studies. Data volumes, detector complexity, and precision required in calculations and simulation will continue to grow in near- and far-future experiments and surveys. The size and complexity of the software and computing effort has grown to be commensurate with that of the experimental instruments. Projects may also need software-detector co-design to optimize physics performance at a minimum detector and computing cost. S&C has evolved to be an increasingly collaborative and global effort across projects, frontiers, and fields, thus work should be coordinated with worldwide partners.

At the same time, S&C technologies are changing the face of HEP. We have solidified the trend towards computing hardware heterogeneity and specialization, and increased use of high-performance computing facilities. AI/ML was neither on the horizon of the 2013 Snowmass process nor in the text of the 2014 P5 report, but it is now an established technology widespread in every HEP area. Quantum computing is

entering the stage as the emerging technology with potential impact on quantum many-body systems, event generators, data analysis, etc.

With all of these considerations, we have focused on a single key recommendation followed by four other key recommendation areas. We now expand on each of these topics.

4.11.1 Coordinating Panel for Software and Computing (CPSC)

The CPSC draws inspiration from the analogous panel in instrumentation. The Coordinating Panel for Advanced Detectors (CPAD), sponsored by APS' Division of Particles and Fields (DPF), *seeks to promote, coordinate and assist in the research and development of instrumentation and detectors for high energy physics experiments* (https://cpad-dpf.org). CPAD was formed around the time of the last Snowmass and serves a number of purposes in the HEP instrumentation community. It is led by an executive committee of about a dozen researchers from universities and national laboratories. Additionally, CPAD has a number of selection committees for awards targeting junior and senior researchers as well as for advising funding agencies. Furthermore, the panel organizes an annual workshop and helps with coordinating various reports (such as the 2020 DOE Basic Research Needs study). For computing in HEP, we envision a CPSC with similar properties and mandate, although the exact details would need to adjust to the different characteristics and requirements of the S&C community. For information, we include a quote from the CPAD mandate, which is recorded in the DPF bylaws:

> *The Coordinating Panel for Advanced Detectors (CPAD) shall consist of a Chair, as well as a Vice-Chair and six members appointed by the DPF Chair-Elect following a call for nominations and approval by the DPF Executive Committee prior to appointment by the Chair-Elect. Panel members shall serve staggered, two-year terms but should not serve more than two consecutive terms. The newly appointed member of the CPAD chair-line shall serve first as Vice-Chair, succeeding to the Chair position in the second year and serving for one year. The CPAD shall have the responsibility to promote excellence in the research and development of instrumentation and detectors to support the national program of particle physics in a global context through the organization of the annual topical meeting on detector research and development; the nomination and selection of the annual DPF Instrumentation Awards and the Graduate Instrumentation Research Award; the promotion of educational programs to further the understanding of detectors and their instrumentation; the organization of multidisciplinary workshops; and the development of new activities consistent with its mission.*

We recommend that DPF append their bylaws to include a similar statement for a CPSC. Central to the CPSC's mission will be to liaise with the funding agencies to ensure that the S&C needs are being met for near-term projects, as well R&D targeting longer-term programs. Additional tasks such as workshops on relevant topics and HEP computing awards would be part of the remit. The panel could also help promote standards and best practices such as publishing and citing software. To be most effective, the CPSC should have explicit connections to existing organizations, such as experiments and collaborations, the HSF, and DOE/NSF funded centers and institutes, which could be achieved through liaison positions and/or panel membership. On the other hand, the CPSC should not promote the work of any one research group and it should try to remove barriers to entry (for individuals and groups entering S&C) to the extent possible. Early career researchers should be represented or otherwise encouraged to participate. The CPSC will need a particularly broad membership because it will need to cover the needs of both experiment and theory. The CPSC should not provide funding for projects.

4.11.2 Long-term Development, Maintenance, and User Support of Software

In addition to existing grants for short term R&D, we need mechanisms for longer term S&C support. This includes personnel to work on long-term code development, maintenance, and user support as well as hardware, such as through computing allocations (storage and computing power), that can support multiyear/long-term software projects. Many projects in need of long-term development are also applicable across multiple experiments/projects and so support is harder to identify with existing structures (such as experimental operations programs), but the reward is also large. In a recent survey of the community, a majority of the respondents believed that software maintenance is underfunded [88]. Some, but not all, work in this area could be covered through an expansion of and coordination between experimental operations programs.

One software package that came up in almost every one of the Computational Frontier events organized as part of the Snowmass process is `Geant4`. This is an essential tool that large and small experiments across frontiers use to develop future detectors and for modeling existing instruments. At the moment, most of the US support for `Geant4` developers comes through large experiments in the energy and neutrino frontiers. The challenge is that this does not easily allow for longer-term development independent of a specific experiment's acute needs and it also makes it difficult for smaller experiments (that often cannot support `Geant4` developers) to influence the future of the program.

A related topic is the long term development of event generators. These tools lie somewhere between theory and experiment, making their support even more complicated. The physics development of event generators requires work on theoretical models, but the packaging, maintenance, and user support of these critical software tools is computational work that may not be valued by the theory community. There are also many common physics and computational challenges associated with event generators that could be served well by common efforts undertaken by a diverse and cross-cutting collaboration, similar to MCNet (https://www.montecarlonet.org) in Europe, which could bring together the U.S. event generator community, and facilitate the sharing of resources and ideas.

There are also a number of experimental tools that are used by multiple experiments where no one experiment is responsible for their long-term development, maintenance, and user support. Examples of this include the reconstruction frameworks (e.g., `LArSoft` [https://larsoft.org] and `ACTS` [https://acts.readthedocs.io]), data processing frameworks (e.g., `Gaudi` [https://gaudi-framework.readthedocs.io]), and production systems (e.g., `Rucio` [https://rucio-ui.cern.ch]). There is also the ubiquitous data analysis framework `ROOT` (https://root.cern.ch), and there is now a growing reliance on other community tools from the scientific `Python` ecosystem like `Numpy` (https://numpy.org) and `SciPy` (https://scipy.org). Given the reliance of HEP science on these general packages, it may be a wise investment for HEP to contribute to their long-term development, maintenance, and user support.

Another critical area is the modernization, maintenance, and user support of S&C for legacy data. Running experiments and surveys have infrastructure to support the interoperability of data products, mostly for internal consumption, but this varies by subfield. However, the data from HEP experiments often have utility long after the instruments are no longer taking data. Empowering (re)analysis of legacy data is not a one time cost and requires modest, long-term support beyond the lifetime of an experiment[4]. The physics benefit could be significant, especially as new insight is developed and as future experiments are planned.

[4]Legacy data preparation can also begin with Open Data initiatives before the end of an experiment.

4.11.3 Cross-cutting Software and Computing R&D

Many HEP software and computing tools are broadly useful, while researchers developing these tools tend to be supported or otherwise directly connected to a single project in a particular frontier. However, many computational methods and tools are broadly applicable across HEP and computational HEP as a discipline can catalyze cross-talk between HEP subdomains.

Enhancing (in contrast to maintaining) the tools from the previous section provides a class of important examples of an impactful investment in cross-cutting R&D. Another class of examples is advanced statistical methods, including machine learning, that can be applied to multiple HEP subdomains. Like event generators, R&D in this area is also between theory and experiment and often does not have a natural mechanism for continual support. There is an urgent need to construct support mechanisms for cross-cutting Data Science within HEP, where researchers can develop, adapt, and deploy new methods to make the most of HEP data and simulations. Deploying state-of-the-art methods may also require innovative hardware solutions that often transcend existing project boundaries. Institutions like the DOE Center for Computational Excellence (HEP-CCE), the NSF Institute for Research and Innovation in Software for HEP (IRIS-HEP), and the NSF AI Institutes (IAFAI [https://iaifi.org] and A3D3 [https://a3d3.ai]) are great examples of interdisciplinary R&D in this area and these should be continued and expanded. Support at smaller scales (e.g., through individual PIs) is also important for a sustained effort. In order to make the most of cross-cutting investments, there should be a plan to connect proof-of-principle research to applications.

Enabling cross-cutting S&C R&D requires access to computational resources that are accessible. A key challenge for cross-cutting R&D teams is that they may not have access to computing allocations or common computing environments. This should be addressed to ensure the success of research in this area.

Cross-cutting S&C innovation can lead to significant jumps in performance, to enable science that was not possible before or to deliver physics results with significantly fewer resources than before. This may lead to new discoveries, shorten the time from producing publication quality results, and reduce our carbon footprint.

Developments in this area (especially in the areas of machine learning and quantum computing) may also have broader implications beyond HEP, where HEP researchers may be able to make contributions with strategic and economic importance.

4.11.4 Heterogeneous Computing

A growing fraction of HEP computing will be provided by hardware accelerators and/or distributed CPU machines from diverse sources (university cluster, HPC, grid, commercial cloud, etc.). We have an opportunity to make the best use of these resources by investing in personnel for code re-engineering and adaptation. These personnel could be HEP scientists who are trained in code portability and/or software engineers. In either case, a unique set of skills are required that are often not part of the standard HEP S&C background.

Fortunately, the HEP community has some collective experience with porting software to be compatible with HPC resources, including with hardware accelerators. In addition to many efforts within experiments and surveys, large and small, there are a number of dedicated programs such as the DOE Exascale Computing Project (ECP), HEP-CCE, Scientific Discovery through Advanced Computing (SciDAC), Computational HEP (CompHEP) more generally, and the NSF IRIS-HEP. In addition to these programs, there are others like the NERSC Exascale Science Applications Program (NESAP) that have supported projects with personnel

and early computing allocations. Some of these projects are supported directly or in part by HEP (through the DOE Office of Science HEP program, the CompHEP subprogram and the NSF Elementary Particle Physics programs) and some efforts are supported through the DOE Advanced Scientific Computing and the NSF Office of Advanced Cyberinfrastructure programs. Continuing and expanding programs across the HEP community and for projects of various scales will be critical in the future.

Training, Career Development, and EDI

First and foremost, research in S&C should be recognized as physics research, analogously to R&D in instrumentation. Correspondingly, there should be a clear career path in Computational HEP from undergraduate courses and research experiences to graduate school programs all the way to faculty and (physics) staff positions. Additionally, researchers who do not make Computational HEP their focus will still need training in S&C. Acquiring these skills should be part of our undergraduate and graduate educations in both experiment and theory. Summer schools and other limited-scope training events can help augment the skill sets, but do not replace coursework.

We hope that elevating the physics recognition for S&C within HEP, will lead to the creation of tenure-track faculty and staff positions. While funding agencies cannot directly create faculty lines, they could catalyze the creation of faculty positions through joint or bridged positions[5] with national laboratories. This could be an effective tool for encouraging new positions, but we should be aware of the additional demands on the researchers for serving two departments/institutions instead of one. The creation of cross-cutting tenure-track staff positions at national laboratories is another effective strategy.

Second, and equally important, we need to eliminate barriers for researchers with diverse backgrounds to work on S&C and we need to create an environment that will retain this workforce. To this end, the CPSC should establish a committee to study the status and challenges related to diversity, equity, and inclusion within S&C in HEP. There will be some challenges that are common with HEP more generally, but there may also be properties of S&C that require specific attention. The committee should present a list of actionable items to the CPSC leadership for implementation in coordination with the broader S&C community.

4.12 Conclusions and Outlook

Software and computing technologies are evolving rapidly and it is hard to imagine what the state of the art will be at the time of the next Snowmass in about a decade. However, it is clear that the trend towards more heterogeneity and a diversity of software tools will continue, triggering the need for a HEP workforce with a correspondingly diverse set of skills and backgrounds.

S&C traverses all areas of HEP. While we have organized the Computational Frontier along cross-cutting topics, there are strong connections to all other Snowmass frontiers. Experimental projects, large and small, in the Energy, Neutrino, Rare Processes and Precision, and Cosmic Frontiers will continue to rely on S&C to deliver the best physics output from our instruments at a variety of latencies and bandwidths. Many areas of HEP simulations and theory more generally also have stringent computational requirements. There are also strong and growing connections to the other Snowmass Frontiers, including the Accelerator Frontier (e.g., accelerator control and modeling), the Instrumentation Frontier (e.g., experimental design), the Underground

[5] Researchers are hired as regular faculty, but typically 50% of their time is covered by a national laboratory through tenure.

Facilities Frontier (e.g., quantum computing), and the Community Engagement Frontier (e.g., training and industry connections).

It is our hope that the establishment of a Coordinating Panel for Software and Computing (CPSC) will serve the community on timescales commensurate with the rapid evolution of S&C technologies. An important function of this panel is to provide guidance to the funding agencies with input from the domestic and international HEP communities. Advances in S&C have been essential to progress in both experiment and theory. Working together as a unified community, we can ensure this continues in the future.

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5

Cosmic Frontier

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Executive Summary

The Cosmic Frontier realizes the High Energy Physics (HEP) community's goal of understanding the fundamental physics that governs the Universe and its constituents through a rich scientific research program designed to *delve deep*, *search wide*, and *aim high* towards discovery. Cosmic observations are exclusively responsible for our knowledge of the need to extend the Standard Model to describe dark matter, dark energy, and cosmic inflation. As a result, the Cosmic Frontier is uniquely positioned to shed light on these mysteries. These efforts have led to tremendous advances in recent decades, including discoveries that the Universe appears to have experienced a period of early exponential expansion with quantum fluctuations seeding later large-scale structures, that the growth of these cosmic structures is influenced by the dynamics of dark matter and dark energy, and that the Universe is again expanding at an accelerating rate today. The Cosmic Frontier research portfolio presents opportunities for large, medium, and small projects that will leverage new developments in both technology and theory to produce a continuous stream of high-impact science over the coming decades.

Cosmic surveys are the primary means by which we can study the origin, structure, composition, and evolution of our Universe. Future surveys will explore its development from the earliest moments and potentially shed light on the connection between gravity and quantum mechanics; these surveys *aim high* to study the Universe under extreme conditions that are impossible to achieve in terrestrial laboratories. Proposed experiments can simultaneously provide precision measurements of dark energy, determine the energy scale and dynamics of cosmic inflation, search for new light relics and other Beyond the Standard Model physics, and probe the nature of dark matter.

New technologies, as well as advances in theory and simulations, are providing exciting opportunities to advance our understanding of the fundamental physics that governs the Universe. Current and near-future large wide-area optical/near-infrared imaging and spectroscopic surveys, proposed cosmic microwave background and spectroscopic survey projects of unprecedented power, and pathfinders for future gravitational wave and line-intensity mapping experiments will greatly extend our scientific reach. New messengers such as gravitational waves provide unobscured views of the Universe at its earliest moments, and could reveal

new physics through dynamical processes such as early phase transitions. Substantial investment in the next generation of cosmic surveys should be a priority to advance the broad range of profound science that only they can address.

Understanding the identity, nature, and origin of dark matter is one of the grandest challenges in physics and spans all Snowmass frontiers. Well-studied theoretical models provide a compelling scientific case to make broad and rapid inroads into unexplored dark matter parameter space via a *search wide, delve deep* strategy. With new experiments that will come online in this decade, the HEP community will search wide to efficiently probe broad, logarithmic ranges of parameter space, including hidden sectors and axion-like particles, deploying experiments that exploit new cosmic probes and cutting edge technologies. Concurrently, the community will delve deep to comprehensively explore the high-priority science targets of weakly interacting massive particles and the QCD axion. Given the importance of dark matter and the broad range of opportunities, aggregate investment in a coordinated dark matter program that spans a wide variety of direct, indirect, and cosmic probe experiments at multiple scales should be a priority with overall funding comparable to that of other large experimental programs, though distributed over a number of complementary efforts.

The HEP community has identified potentially transformative opportunities to address fundamental physics questions via Cosmic Frontier programs. We aspire to **Aim High**, **Search Wide**, and **Delve Deep**:

- Complete the CMB-S4 cosmic microwave background experiment and build a large spectroscopic facility (Spec-S5) to study physics including inflation, dark energy, light relics, modifications to general relativity, and dark matter.

- Pursue a broad program investigating the full landscape of dark matter candidates, including implementation of the existing Dark Matter New Initiatives (DMNI) portfolio and development of future DMNI-like programs focused on small projects; investment in new quantum technologies; and engagement of the HEP community in the development and execution of cosmic and indirect searches for dark matter, to take full advantage of the unique opportunities provided by cosmological and astrophysical probes (e.g., Rubin LSST and AugerPrime).

- Scale up mature technologies for weakly-interacting massive particle (WIMP) direct detection, fully exploring the parameter space down to the neutrino fog, and support high-energy gamma-ray telescopes (e.g., SWGO and CTA) to probe thermal WIMPs up to tens-of-TeV mass scales. Move ahead with new, construction-ready DMNI experiments with the capacity to probe the QCD axion over most of its viable mass range.

Fully realizing the scientific potential of this exciting experimental program will require support for a range of non-project research activities, including theory studies and simulations, funding for analysis including cross-experiment joint efforts, and the acquisition of key complementary datasets (e.g., follow-up observations to enable supernova and gravitational wave source cosmology; spectroscopy for photometric redshift training and calibration; and measurements of dark matter density distribution and astrophysical backgrounds to inform direct and indirect dark matter searches). To take maximum advantage of the remarkable datasets produced by the cosmic frontier projects, the science collaborations analyzing these data will need funding for both scientific infrastructure and research activities.

5.1 Search Wide, Aim High, Delve Deep: the Cosmic Frontier Strategy for Discovery

The Cosmic Frontier (CF) comprises a broad set of activities aimed at understanding the fundamental physics which governs the evolution of the Universe and its constituents. For Snowmass 2021, the CF is organized into topical groups, each of which produced a report summarizing the open questions and scientific opportunities in its area:

- CF1 : particle-like dark matter [1];
- CF2 : wave-like dark matter [2];
- CF3 : cosmic probes of dark matter [3];
- CF4 : dark energy and cosmic acceleration in the modern Universe [4];
- CF5 : dark energy and cosmic acceleration at and before cosmic dawn [5];
- CF6 : new facilities and complementarity in probes of dark energy and cosmic acceleration [6]; and
- CF7 : cosmic probes of fundamental physics [7].

Taken together, the topical working group reports present a broad program of inquiry that offers unique opportunities to understand the physics of dark matter, dark energy, and inflation, and to search for physics Beyond the Standard Model (BSM) in a way that is highly complementary to the other Snowmass frontiers.

The Cosmic Frontier engages with all five of the 2014 P5 science drivers, with particular connections to: (i) identify the new physics of dark matter; (ii) understand cosmic acceleration: dark energy and inflation; and (iii) explore the unknown: new particles, interactions, and physical principles. Currently, the incontrovertible experimental evidence for physics Beyond the Standard Model of particle physics consists of:

- dark matter;
- dark energy;
- cosmic inflation;
- the baryon asymmetry of the Universe; and
- neutrino masses and mixing.

With the exception of neutrino masses, all of these are the direct result of observational data from the Cosmic Frontier. Moreover, the techniques of the Cosmic Frontier remain the only currently established way to access several of these BSM physics topics. The successful road map laid out by P5 in 2014 has resulted in a remarkable period of investigation into fundamental physics through CF projects, which have made great progress exploring the parameter space of dark matter models and pinning down the nature of dark energy. There is strong motivation to build and expand upon that vision to complete exploration of the physics of dark matter, dark energy and cosmic inflation, as well as to search for new physics that is too massive, too weakly-interacting, and/or requires too high energies to access terrestrially. A discovery in any of these areas would be transformational for particle physics, and would suggest new priorities for HEP research across all the Snowmass frontiers in the future.

5.1.1 Fundamental Questions

CF projects engage with fundamental questions that are at the core of the quest to extend/replace the Standard Model and are well-aligned with the 2014 P5 science drivers .. A non-exhaustive list of the central questions includes:

- What is the nature of dark matter? Is it a single particle or a set of multiple components? Does it belong to a dark sector?
- How does dark matter interact with the Standard Model? Does the Higgs serve as a portal between the two? Are there new bosonic mediators?
- Is the dark matter itself bosonic and does it exhibit macroscopic wave-like phenomena like oscillatory forces?
- What are the dynamics within the dark sector? Does dark matter have important self-interactions?
- How was the dark matter produced in the Early Universe?
- Does the nature of dark matter reveal further secrets informing physics Beyond the Standard Model or cosmology?
- What is the nature of dark energy? Is the present acceleration due to a new energy density component or does it demand a change in general relativity?
- If dark energy is an energy density, is it a cosmological constant, or a dynamical quantity changing with time?
- When did dark energy become important in the history of the Universe?
- Why are there two eras of acceleration in the history of the Universe?
- How is the inflationary paradigm realized in nature?
- What is the energy scale of inflation?
- Does inflation have dynamics that manifest themselves as an observable imprint on the primordial distribution of matter fluctuations?
- Did BSM degrees of freedom influence the thermal history of the Universe?
- What is the scale of neutrino masses? Can cosmological observations sufficiently constrain it to distinguish between normal and inverted mass hierarchies?
- Can gravitational waves reveal new dynamics or early cosmological phase transitions?
- How can cosmic sources of high energy particles reveal their participation in new interactions or new physics?

5.1.2 State of the Cosmic Frontier

Since the previous Snowmass in 2013, the Cosmic Frontier has made great progress towards realizing the science goals prioritized by P5 in 2014. Searches for WIMP dark matter scattering with nuclei have advanced to Generation-2, and searches for axions have begun to probe the parameter space relevant to explain the strong CP problem. These searches 'delve deep' to study some of the high priority accessible targets in dark matter parameter space. At the same time, new techniques such as those sensitive to electron scattering are able to probe dark matter to sub-MeV masses and 'search wide', providing coverage for a wide parameter space consistent with dark matter production in the early Universe.

The current U.S. priority on quantum information science has produced fruitful collaborations between HEP and researchers in other fields, as ultra-weakly interacting dark matter is a natural science target for quantum sensing. Cross-disciplinary collaborations with the atomic, molecular, and optical (AMO) and condensed matter fields have also produced novel dark matter search techniques to provide broad coverage of dark matter parameter space.

Indirect searches for dark matter using the Galactic center, Milky Way dwarf galaxies, and our local Galactic halo as observational targets have produced broad constraints on dark matter mass and self-annihilation cross section. However, despite a strong endorsement from the previous P5, indirect searches for dark matter with gamma-ray observatories have not been prioritized and the U.S. is ceding leadership in this area to other countries.

Investments in optical cosmological surveys are now coming to fruition – results from the Dark Energy Survey (DES) and BOSS/eBOSS surveys have cemented ΛCDM as a description of the expansion of the Universe, the Dark Energy Spectroscopic Instrument (DESI) is obtaining data at a phenomenal rate, and construction of the Vera C. Rubin Observatory is nearing completion. These experiments 'aim high', offering unprecedented opportunity to understand the nature of cosmic acceleration/dark energy as well as providing unique probes of the properties of dark matter such as self-interactions. In addition to these powerful ground-based, U.S. led surveys, there are also space missions and other large ground-based cosmology projects being carried out by other communities world-wide. Ensuring a return on the investment that was made in these Stage IV facilities by the U.S. community requires that the science collaborations analyzing these datasets have robust funding for both scientific infrastructure and research activities.

Major advances have also been made in cosmic microwave background (CMB) science including tight constraints on the physics of the early Universe that broadly support inflation, and rule out once plausible theories; constraints on BSM particles (light relativistic species); and tight constraints on ΛCDM. The U.S. CMB community has coalesced around a single, large next-generation project, CMB-S4, which will observe the microwave sky with unprecedented statistical precision, targeting the physics of cosmic inflation, searches for BSM dark radiation, and measuring neutrino masses.

The detection of gravitational waves from merging binary neutron stars and black holes by the LIGO and Virgo Collaborations was a watershed moment for cosmic science. This new observational tool will be important for many areas of particle astrophysics and cosmology including measurements of cosmic acceleration at high redshift, searches for dark matter, and detection of relic gravitational wave radiation from early Universe phase transitions.

5.1.3 Science Opportunities

We identify science opportunities across the broad themes of dark matter detection, discovering the physics of inflation, precision cosmology for understanding both dark matter and dark energy, and the use of gravitational waves and high energy cosmic particles for these HEP science goals.

- **CMB probes of inflationary cosmology**: Completion of CMB-S4 will confirm or rule out large classes of models of cosmic inflation, pinpoint or limit the energy scale of inflation, and probe the dynamics of this ultra-high-energy sector.

- **CMB probes of dark radiation / light thermal relics**: CMB-S4 will discover or rule out new light relics during and after the QCD phase transition era, and uniquely probe a large parameter space for light particles Beyond the Standard Model of particle physics.

- **CMB probes of neutrino physics**: CMB-S4 will constrain the neutrino mass scale, including potential sensitivity to the normal/inverted mass hierarchy, and explore other neutrino properties Beyond the Standard Model of particle physics. Further advances in CMB physics will eventually be enabled by planning and executing CMB-S5.

- **Precision cosmology with existing telescopes**: Cosmic surveys including DESI and the Rubin Observatory Legacy Survey of Space and Time (LSST) will provide strongly-constraining data sets for precision cosmology. One percent measurements of the dark energy density to $z \sim 1.5$ will provide crucial tests of dynamical dark energy models. Measurements of the overall matter power spectrum will enable tests for new dynamics in the early Universe and for precision constraints on the total mass of neutrinos. By probing both the growth rate of density perturbations and the expansion history of the Universe, these experiments will provide important tests of whether cosmic acceleration is in fact due to a dark energy-like component of the Universe or if it instead requires a non-Einsteinian theory of gravity on cosmic scales. Increased statistics for Milky Way dwarf galaxies and studies of smaller dark halos will provide information on dark matter masses and self-interactions and also provide new targets for indirect detection searches. For these surveys to reach their full potential, funding for innovative science analyses – including simulations and cross-survey measurements – will be needed. New data from other facilities will be needed as a complement to unlock the full constraining power of LSST, including follow-up observations of strong gravitational lenses, supernovae, and gravitational wave standard sirens, as well as measurements of spectroscopic redshifts for deep training samples of objects to enable precision photometric redshift measurements.

- **Stage V spectroscopic probes of cosmic acceleration and inflationary cosmology:** The development of a powerful new Stage V spectroscopic facility (Spec-S5) will allow precision measurements of the cosmic expansion history to be extended to the limits of the modern Universe ($z \lesssim 5$), simultaneously providing new constraints on the inflationary epoch of cosmic acceleration. Accessing high redshifts greatly expands the cosmic volume surveyed, enabling structures on the largest scales where inflationary signatures are expected to manifest to be explored. A Stage V spectroscopic facility also enables a search for new light relics and other Beyond the Standard Model particles including measurement of the sum of the masses of neutrinos, and probes of the physics of dark matter via a variety of precision studies of nearby galaxies and of stars in the Milky Way halo.

- **New pathfinder experiments for Stage VI precision cosmology**: Pathfinder experiments will enable progress on powerful new probes of cosmology such as line intensity mapping methods in 21 cm and millimiter wave molecular lines. Those new probes can extend matter power spectrum studies to

still higher redshifts and greater volumes than Stage V spectroscopy can reach. For example, LuSEE-Night is a mission to the far side of the Moon being carried out in partnership between DOE and NASA as a pathfinder for a future Stage VI neutral hydrogen 21-cm experiment.

- **Direct detection of WIMP dark matter**: The next generation of direct dark matter experiments will be able to probe the WIMP paradigm down to and into the "neutrino fog" over several orders of dark matter mass, using a combination of scaling up existing technologies and exploring new detector concepts.
- **Direct detection of axion dark matter**: A portfolio of axion dark matter search experiments enabled by new quantum sensing technologies will "delve deep" in searches for the ultraweak QCD axion signal in most of its predicted band. The Dark Matter New Initiatives (DMNI) has identified promising small projects to explore wide swaths of the parameter space.
- **Cosmic probes of dark matter**: Cosmological and astrophysical observations, coupled with numerical simulations and theory, will widely probe and constrain the fundamental nature of dark matter over an expansive range of parameter space, some of which is inaccessible to terrestrial and laboratory searches. In the coming decade, Rubin LSST and DESI have the potential to revolutionize our understanding of microscopic properties of dark matter, such as mass, self-interactions, interactions with radiation, and quantum wave features. On a longer time horizon, CMB-S4 and a planned stage V spectroscopy project will have access to rich dark matter physics as well. The inclusion of dark matter physics in the research programs of these experiments (together with necessary investments in theory and simulation) alongside studies of dark energy and inflation should be strongly supported.
- **Indirect detection of dark matter via high energy astrophysics**: New > 100 GeV gamma ray observatories including CTA will study dark matter via its annihilations or decays, with sensitivity to the thermal freeze-out benchmark annihilation rate up to masses approaching the 100 TeV scale, where model-agnostic limits on the early Universe cross section come into play. Planned or proposed space missions will set stringent new bounds in the keV-GeV range, and new cosmic-ray detectors will perform the first dedicated searches for low-energy antinuclei as a background-free discovery channel. Planned and ongoing upgrades to existing observatories including IceCube and AugerPrime will provide unique probes of ultra-heavy dark matter.
- **Multi-pronged detection of low mass dark matter in dark portal scenarios**: A variety of new techniques including low-threshold microcalorimetry will be deployed to search for sub-GeV portal dark matter. Concurrently, accelerator-based experiments will search for dark matter production and for new bosons which serve as the messengers between the dark and visible sectors. The DMNI has identified promising small projects to advance these searches into motivated regions of parameter space.
- **Direct detection of ultralow mass dark matter using cross-disciplinary technologies**: Engagement with the fields of quantum information science and atomic, molecular, and optical physics has brought new ideas and technologies to bear on searching for ultra-low-mass wave-like dark matter, which produce periodic perturbations detectable via ultra-sensitive instruments such as atomic clocks and interferometers.
- **New experimental windows on fundamental physics**: Pathfinder experiments including multi-messenger cosmology with gravitational waves, new techniques for precision measurements in astrometry, spectroscopy and photometry, and new sky surveys from space at radio frequencies below Earth ionospheric cut-off have potential to unlock hitherto unused probes of fundamental physics through cosmological measurements.
- **Ultra-high-energy cosmic rays as a probe of new physics up to and beyond the GUT scale**: The new level of precision achieved by AugerPrime, IceCube, and next-generation experiments

(GCOS, GRAND, POEMMA, and IceCube-Gen2 with its surface array) will provide opportunities to study non-perturbative QCD and physics Beyond the Standard Model using natural accelerators well beyond the reach of human-made ones. The already-established anomalous muon production in extensive air showers (which has eluded explanation in models tuned to LHC data) guarantees that discoveries will be made.

- **Gravitational waves as a new probe of particle physics and cosmology**: Gravitational waves have emerged as a new and unique probe of dark sector physics, especially if the dark sector is only minimally coupled to the Standard Model via gravity. In addition to searching for relic gravitational waves from early Universe phase transitions (including leptogenesis models or the QCD axion) and measuring the equation of state of quark matter at high density in neutron stars, current and future gravitational wave observatories promise a powerful new means of performing precision measurements of cosmic acceleration through a new class of standard distance indicators based on mergers of neutron stars and black holes. These large interferometers also have a large effective collection area, enabling searches for ultra-heavy dark matter.

- **High-energy neutrinos as a new venue to study neutrino interaction and mixing**: The cosmic neutrinos detected by IceCube provide a new opportunity to learn neutrino physics at TeV-PeV energies. The upcoming IceCube Upgrade and future GeV cosmic neutrino experiments will measure the flavor composition and tau neutrino appearance with high precision. Future >100 PeV neutrino experiments may uncover cosmogenic neutrinos and probe BSM features at extreme energies.

5.1.4 The Experimental Program

The CF strategy detailed in this report encompasses a science-rich program with small, medium, and large experiments which are planned on both near-term and long-term timescales. The community consensus is that strong support for this entire program is essential to assure that HEP shares in and benefits from the upcoming era of discovery. Groundbreaking precision measurements anticipated in the next two decades, as well as even more powerful experiments to follow, will reach key science discovery thresholds which should be comparable in their impact to the discovery of the Higgs boson. An overview of the CF program is provided in this section. Details about the projects and activities mentioned here are provided in later sections of this report.

Cosmic surveys: Figure 5-1 summarizes the cosmic survey projects and their discovery potential across multiple science areas of our program.

For each fundamental question, we have identified a key measurement with a clear threshold for discovery. Together, the planned projects should deliver results spanning large swaths of cosmic frontier science, including studies of cosmic acceleration/dark energy, inflation, searches for indications of new particles (e.g., dark radiation), and exploration of dark matter properties. Cosmic surveys generally provide datasets that can be used for many purposes, addressing multiple HEP science drivers simultaneously. The figure shows a rough timeline for when each major project could come into play and gradually reach its full discovery power. The large CMB-S4 project and the next large Stage V Spectroscopic Facility (Spec-S5) should play a key role in advances over the next decade and beyond. The figure also includes potential future surveys that will be enabled by near-term R&D and small pathfinder initiatives; these projects would employ new technologies and techniques such as 21-cm and mm-wave Line Intensity Mapping (LIM), Gravitational Wave Observatories (GWO), and future broadband CMB imaging (CMB-S5). Note that Spec-S5, GWO, LIM, and CMB-S5 are categories of future experiments for which multiple proposed projects may currently exist in the community (see the CF4–6 reports [4–6] and reference therein for details). This planned sequence

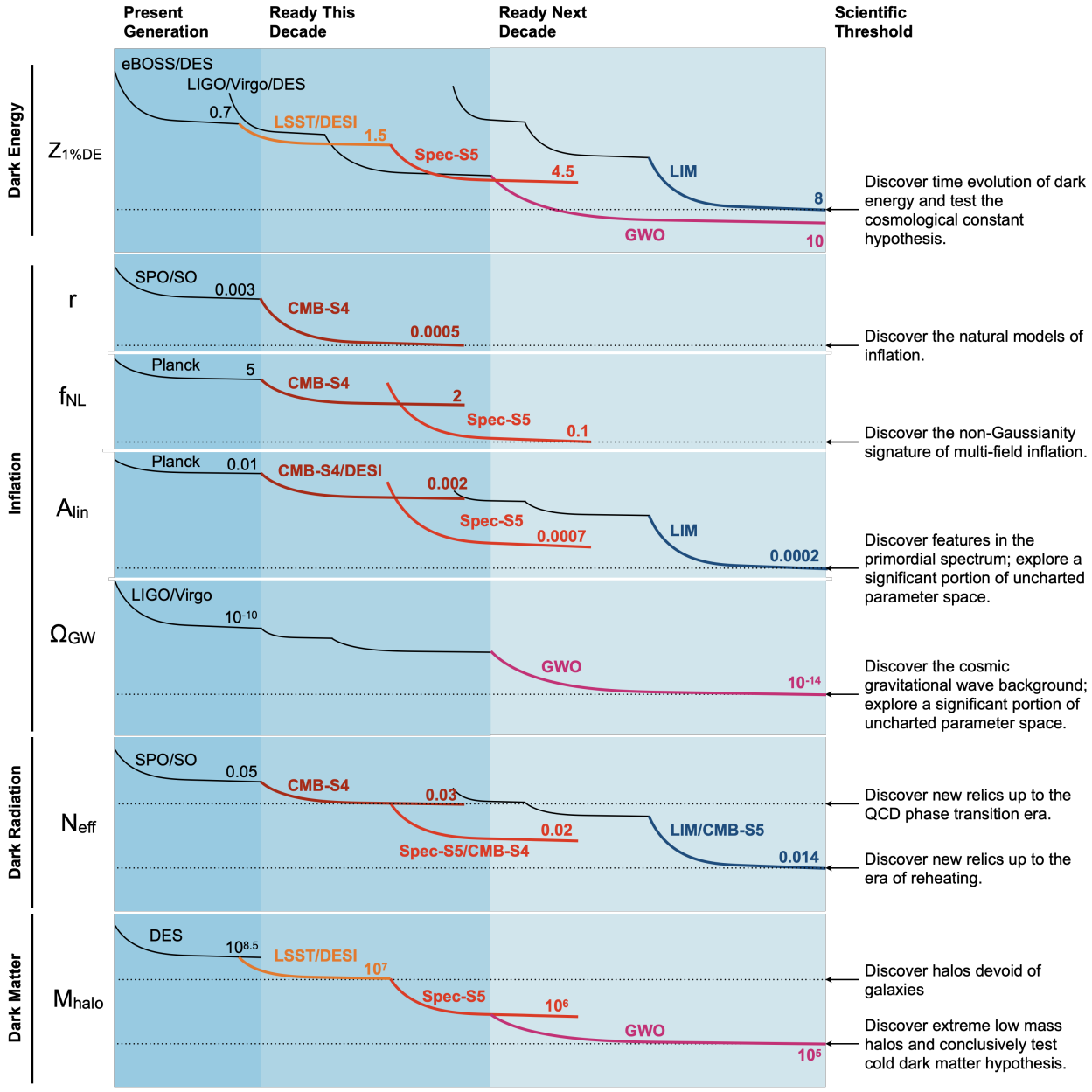

Figure 5-1. *The landscape of cosmic survey projects and their discovery potential. For each major science topic, we identified a key measurement threshold for discovery. Bold lines show medium and large projects ready to produce science in this decade or the next. In particular, CMB-S4 is a large project currently with CD-0 and progressing to CD-1. Labeled thin lines represent the results from current surveys and unlabelled thin lines are pathfinders for the next generation of projects. Note that the labels Spec-S5, GWO, LIM, and CMB-S5 do not represent specific projects. Instead, they represent categories of future experiments for which multiple proposed projects may currently exist in the community: a Stage V Spectroscopic Facility, next-generation gravitational wave observatory, 21cm/mm-wave line intensity mapping, and next-generation CMB, respectively. Adapted from the CF5 report [5].*

of experiments ensures that CF will have a continuous stream of data to support scientific breakthroughs without gaps during the construction of the largest facilities.

In the Cosmic Frontier survey ecosystem each type of program brings unique strengths to the portfolio, including galaxy shape measurements that can only come from imaging, precise and robust redshift measurements that require spectroscopy, and multi-messenger data that exploits new gravitational wave detection capabilities; by also spanning a range in wavelength (e.g., Optical/IR vs. mm-wave vs. 21-cm), information from different redshift ranges can be accessed. While each survey will deliver groundbreaking results on its own, no single experiment can meet all of the discovery thresholds without complementary information from other parts of the program. The surveys complementary information provide both systematic rigor and complete coverage of the scientific goals. This diverse portfolio of multiple experiments is, thus, required to achieve the scientific reach of the program.

As a result, the CF survey program is designed to leverage the strengths of multiple experiments simultaneously. One example of this complementarity is that to go beyond discovery of the energy scale of inflation (which CMB-S4 could accomplish on its own) to conclusively probing its physics via precision measurements of the $f_{\rm NL}$ parameter, we would require measurements from a Stage V Spectroscopic Facility (Spec-S5). Experiments using well-developed techniques, like CMB-S4 and Spec-S5, are ready to be immediately implemented, driving forward our understanding of inflation and dark energy in this decade. Other science goals such as studying the time evolution of dark energy, conclusively testing the cold dark matter hypothesis, searching for features in the primordial power spectrum, and discovering the cosmic gravitational wave background will require the next-generation of surveys for which pathfinders and R&D work should be supported in this decade. These and many other science opportunities realized by the CF's survey ecosystem have been discussed in detail in the topical group reports [3–6]. In any funding scenario to be considered by the next P5, the Snowmass community consensus is that support for the CF cosmic surveys program should be at a level that enables discovery across the entire scope of the science program.

Note that in Figure 5-1 the scientific thresholds for dark matter and dark energy are parametrized by the smallest dark matter halo mass ($M_{\rm halo}$) and the highest redshift ($z_{1\%\rm DE}$) out to which the contribution of dark energy to the total mass-energy density of the Universe can be detected with percent-level precision, respectively. The discovery threshold for features in the primordial spectrum due to the physics of inflation is given in terms of the parameter $A_{\rm lin}$. The primordial gravitational wave background discovery threshold is represented by the parameter $\Omega_{\rm GW}$. For the inflation science parameters corresponding to the energy scale (r) and the non-Gaussianity features ($f_{\rm NL}$), we have $r < 0.001$ as the threshold that would rule out models that naturally explain the spectral index n_s within Planck characteristic scales while $f_{\rm NL} > 1$ is the discovery threshold for models of simple single field inflation. These, in turn, translate into sensitivity thresholds for experiments: $\sigma(r) = 0.0005$ and $\sigma(f_{\rm NL}) = 0.1$, which are the values shown in Figure 5-1. The rationale for new radiation in the early Universe is similar: the threshold for light thermal relics out to 100 GeV is $\Delta N_{\rm eff} = 0.06$ and for exclusion of all thermal light relics it is $\Delta N_{\rm eff} = 0.027$. These correspond to sensitivities of $\sigma(\Delta N_{\rm eff}) = 0.03$ and $\sigma(\Delta N_{\rm eff}) = 0.013$, respectively.

Searching for dark matter: Figure 5-2 shows two snapshots of the key dark matter discovery parameter space, which has greatly expanded since the last Snowmass. They illustrate the broad coverage spanning many decades of dark matter parameters which will be achieved by the ambitious experimental program envisioned in this report, comprising both a broad portfolio of small/medium-scale direct and indirect detection experiments optimized for each decade in dark matter mass, as well as an expanded cosmic probes program to identify the properties of dark matter via cosmic surveys, which is highly synergistic with the other science these surveys will undertake. The top panel shows current experimental limits via the grey shaded regions, while the bottom panel shows the projected sensitivity over the same parameter space after completion of our program. In many cases, utilizing new detector technologies will require cross-disciplinary collaborations to access the expertise, technology, and facilities of neighboring fields of study such as AMO,

condensed matter physics, quantum information science, and gravitational physics. Similarly, for indirect probes of dark matter scattering, annihilation, or decay in galactic halos, HEP provides a critical role in developing instrumentation for astroparticle observatories. Understanding the astrophysical backgrounds to these searches will require engagement and collaboration with the broader non-HEP astronomy and astrophysics community.

Accomplishing the full scientific scope of the overall cosmic frontier program will require that robust support for ongoing, new, and future projects be well-matched by funding mechanisms for research groups to do science with data from those projects. This includes research support for teams within experimental collaborations and beyond (e.g., theory, computing, simulation developments as well as detector R&D studies that may not be part of an existing experiment in our portfolio today, but that will enable the next generation of experiments). Even for ongoing experiments, a strong feature of the CF program is that coordinated analyses of data from multiple projects can yield results of greater impact than the sum of their parts. Thus, new mechanisms to support such cross-project initiatives will be an important component of the CF strategy for discovery.

5.2 Dark Energy

The accelerating expansion of the modern universe over the last 5 billion years of cosmic history represents one of the most formidable scientific problems of our time. Its discovery was awarded the 2011 Nobel Prize in Physics. Similarly to what has happened after the discovery of the Higgs boson by our colleagues in the energy frontier, this discovery has launched our field into a new era of precision measurement studies aiming to understand the physics of cosmic acceleration — the explanation for which must clearly lie Beyond the Standard Model.

Developing an understanding of the cause of cosmic acceleration in the modern universe should revolutionize our understanding of fundamental physics. Either we will discover a new form of energy whose source lies Beyond the Standard Model of particle physics – some form of dark energy; or we will motivate a new theory of gravity beyond Einstein's general relativity. If dark energy is the solution, it then accounts for two-thirds of the total present mass-energy density of the universe and permeates the empty space between galaxies. It hinders the growth of density perturbations such as those which can form clusters of galaxies, and makes distant astrophysical sources appear dimmer than expected by increasing their distances. Detailed measurements of both the expansion history of the universe and of the rate at which cosmic structures grow are central to understanding the nature of cosmic acceleration; in combination, they allow us to distinguish explanations associated with dark energy from those which require modifications to the theory of gravity.

Cosmology research in the twenty-first century is dominated by large cosmic survey experiments carried out by world-wide collaborations comprising hundreds of members from dozens of institutions. These large teams have developed specialized equipment and novel analysis tools which enable us to carry out observations of unprecedented scope and precision. For example, the Dark Energy Survey (DES) collaboration uses a 570-megapixel camera, the Dark Energy Camera (DECam), installed on a 4-meter telescope in Chile; the Dark Energy Spectroscopic Instrument (DESI) collaboration uses a system of 5000 robotic fiber positioners on a 4-meter telescope in Kitt Peak, Arizona; and the Rubin LSST Dark Energy Science Collaboration (DESC) will use a 3.2 gigapixel camera on a 8.5-meter telescope at the Vera Rubin Observatory in Chile.

As a result of this robust series of cosmic survey experiments, the community has advanced in leaps and bounds towards our goal of understanding cosmic acceleration via precision measurements of key cosmological parameters. These key parameters include:

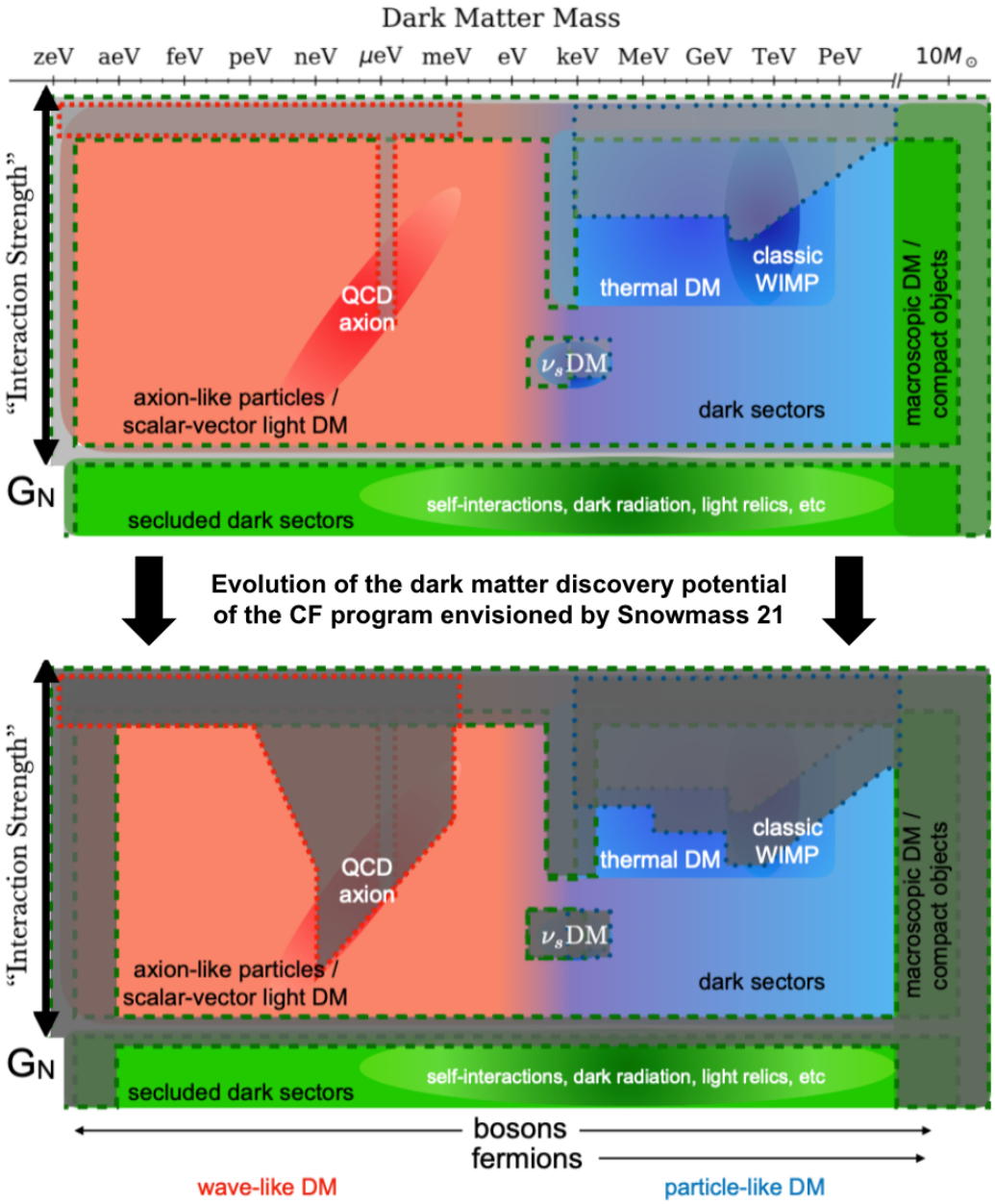

Figure 5-2. *Cartoon (not to scale) of the gains in sensitivity enabled by the search strategy outlined in this report (from light to dark gray shaded regions). Regions where dark matter typically manifests as a wave are shaded in red, whereas regions where it manifests as individual particles are blue. Broad, logarithmic gains in coverage are attainable through a range of newly developed techniques, which will require an ambitious and significantly expanded program of mid- and small-scale experiments as well as novel cosmic probes using existing and planned survey instruments (shaded green). See Section 5.4 for details.*

- **The equation of state parameter of dark energy (w).** — If w is exactly equal to -1 and does not change throughout the cosmic history, then dark energy acts as a cosmological constant – the

simplest, yet non-trivial, dark energy model. One of the key questions that our community wants to shed light upon is whether or not dark energy is consistent with this model. Determining the dark energy equation of state with percent-level precision over a wide redshift range is key for addressing many fundamental questions related to dark energy and cosmic acceleration. Over the past twenty years of CF research cosmic surveys have made huge progress in this area. We now can measure w well at $z < 0.7$; observations so far are consistent with a cosmological constant model, but the time evolution of the cosmic equation of state is only poorly constrained so far. Our next leap will be to study the signatures of dark energy to the limits of the modern universe ($z \lesssim 5$), which will provide novel insights into the earliest times when it began to become significant.

- **The rate of expansion of the universe today (H_0).** — This parameter is related to dark energy because it provides the low-redshift anchor to measurements of the cosmic expansion history. As a result, the value of H_0 has an impact on many constraints on w. H_0 has been determined with good precision by experiments relying on data from two vastly different eras of the universe. Early-universe measurements (using for example CMB observations) would be expected to agree with values derived from galaxies, supernovae and other observables in the dark energy-dominated modern universe. A discrepancy between the two regimes would indicate either that the model is incomplete or that there are systematic issues in the distance determinations used to anchor sets of H_0 measurements. At this point, measurements of H_0 with precision of 1-2% have been made with a variety of techniques; the tension between determinations tied to the low-redshift versus high-redshift distance scales is starting to exceed the 5-sigma level. Several new measurements that will help uncover the origins of this discrepancy over the next two decades are described in this report.
- **The amplitude of fluctuations in the density of matter in the universe (S_8).** — Precision measurements of the amplitude of density fluctuations in the universe and their growth over time are highly complementary to measurements of the cosmic expansion history (which should directly depend on the dark energy equation of state). For instance, if general relativity provides the correct description of gravity on large scales, the growth rate of density perturbations can be predicted directly from the expansion history; however, if cosmic acceleration occurs due to departures from Einsteinian gravity, this relationship is broken. Early and late-universe measurements of the amplitude of the matter power spectrum, as measured by the S_8 parameter, are currently in tension. The significance of this tension is lower than for H_0, but the ongoing CF experimental program is rapidly improving the precision of measurements in this area, and percent-level determinations of S_8 in both the modern and CMB eras will soon be possible.

5.2.1 The Next Stages of Dark Energy Experiments

The dark energy component of the CF program has long been planned to proceed via a series of cosmic survey *Stages*, each greater in scope and precision measurement capability than its predecessor, as defined in the Dark Energy Task Force (DETF) report [8]. The current state-of-the-art results are coming from DETF Stage III surveys (e.g., BOSS, eBOSS and DES); DETF Stage IV experiments are now underway (e.g., DESI) or soon to begin (LSST). These new experiments should provide percent-level constraints on w (for models where its value does not evolve with time), driven primarily by measurements at $z < 1.5$.

Since the last Snowmass report, CMB experiments have become a significant part of the CF program. The next-generation project, CMB-S4, was ranked highly by the previous Snowmass/P5 process and is currently at the CD-0 stage. The data obtained by CMB experiments plays a vital role in exploring the fundamental HEP questions of cosmic acceleration in both the modern universe (dark energy) and the early universe (inflation).

Looking forward, within the next two decades, our community seeks to build CMB-S4 as well as to develop new Stage V and Stage VI projects. This suite of experiments will make precision measurements of w, H_0, and S_8 and other cosmological parameters with data sets that probe not only the current era in which dark energy is firmly dominant, but also detailed measurements going well beyond the transition between the dark matter- and dark energy- dominated eras and new tests of consistency with early universe data.

In this report, we categorize the next stages of dark energy and cosmic acceleration experiments as follows:

- Stage IV – In this category we include those experiments which meet the DETF Stage IV definition (such as DESI and Rubin LSST), as well as fourth-generation CMB experiments. Both classes of experiment complement each other, as the science of early and late-time cosmic acceleration are strongly intertwined. The Stage IV CMB project CMB-S4 is currently under development and should play a key role in cosmic frontier science. Stage IV cosmic survey experiments will provide precision constraints on dark energy, predominantly over the redshift range $z \sim 1.5$ (vs. $z \sim 0.7$ for Stage III). Novel analysis techniques that can take advantage of the leap in constraining power provided by Stage IV experiments, both when they are considered on their own and especially when analyzed in combination, should reduce systematic uncertainties and establish the true significance of the emerging tensions in H_0 and S_8.

- Stage V – In this category we include those experiments that would represent a substantial improvement ($3-4\times$ or better) in capabilities or cosmological constraining power over the equivalent Stage IV experiment. These projects will take the current precision cosmology program to the next level, providing percent-level constraints on the contribution of dark energy to the total density of the universe at redshifts up to $z \sim 5$; enabling new probes of the physics of inflation, with the potential to rule out broad swaths of models and to measure inflationary energy scales; and exploring in depth possible explanations for the origins of the current H_0 and S_8 tensions.

- Stage VI – This category encompasses a future generation of dark energy experiments which can further increase constraining power over Stage V and begin to test cosmology in the 'dark ages' of the Universe at $5 \lesssim z \lesssim 10$. Such projects will require smaller pathfinder efforts now to develop key technologies and methods, which should enable them to become ready to reach project status ~ 10 years from now. These ambitious experiments will incorporate novel technologies and take advantage of new opportunities, driving the field to its next leap in dark energy precision studies. Higher-redshift experiments should be able to explore even larger scales than Stage V, expanding the sensitivity to inflationary signatures, as well as providing sensitive tests for the presence of early dark energy.

5.2.2 A Stage V Spectroscopic Facility (Spec-S5)

When Vera Rubin LSST, DESI, and CMB-S4 data are in-hand, the greatest near-term opportunity to revolutionize our understanding of cosmic acceleration both in the modern universe and the inflationary epoch will be provided by a new Stage V Spectroscopic Facility (Spec-S5). Spec-S5 would feature a large telescope aperture, wide field of view, and high multiplexing. The technology for such a facility is at this point well-developed, building substantially on the legacy of DESI and Rubin Observatory. A Spec-S5 can simultaneously provide a dense sample of galaxies at lower redshifts to provide robust measurements of the growth of structure at small scales, as well as a sample at redshifts $2 < z < 5$ to measure cosmic structure at the largest scales, spanning a sufficient volume to probe primordial non-Gaussianity from inflation and to search for features in the inflationary power spectrum on a broad range of scales, while also testing dark energy models in poorly-explored regimes, determining the total neutrino mass, and strongly constraining

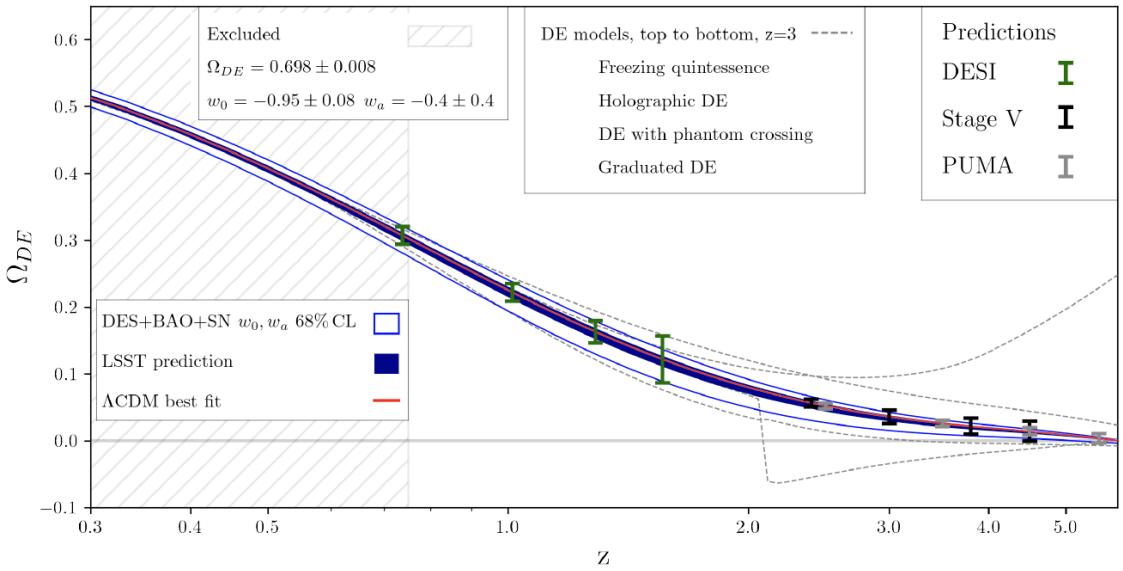

Figure 5-3. *Projected sensitivity to the fractional dark energy density relative to closure density as a function of redshift. Solid lines indicate extrapolations to high redshift of current conventional models fitted to data at low redshift,* $0.1 < z < 0.75$. *Dashed lines indicate predictions of new models designed to address various tensions in existing datasets. Data points with error bars indicate how the how the 2%-level sensitivity that should be obtained in ongoing and future high redshift surveys can directly constrain and discriminate between these models. From the CF4 report [4].*

the effective number of light relics. A Spec-S5 would also be able to probe the nature of dark matter using the kinematics of stars in the Milky Way halo and measurements of the matter power spectrum at small scales.

Multiple options for facilities that would qualify as a Spec-S5 have been proposed [9–12]. These projects, whose concepts are well advanced, are described in the CF4 report [4], which also outlines the key factors to be considered when evaluating candidate facilities. The key requirement is that a Spec-S5 should represent a significant advance over what is possible with Stage IV facilities, should enable transformational progress on all of the Stage V science goals, and open up new discovery space, including:

- Measuring the contribution of dark energy to the total mass-energy density in the universe with uncertainties below 2% of $\Omega_{\rm total}$ out to $z = 5$, redshifts at which dark energy becomes dynamically negligible in w_0/w_a models, while simultaneously constraining modified gravity models over this range; cf. Figure 5-3. Spec-S5 measurements will also provide sensitive tests for early dark energy (at $500 < z < 50000$), as illustrated in Figure 5-4.

- Exploring the physical nature of the tensions in current measurements of H_0 (e.g., via BAO-based measurements spanning an unprecedented range of redshifts) and S_8 (with dense low-z samples providing many cross-checks for systematics by enabling measurements using many separate galaxy populations as well as multiple lensing methods).

- Testing for signatures of non-Gaussianity from inflation at a sufficient precision to be able to rule out all non fine-tuned multi-field models, while simultaneously searching for inflationary primordial features that signal the breaking of scale invariance and constraining contributions from dark radiation (sub-eV particles thermalized in the Universe). The Spec-S5 studies of inflation and dark radiation are

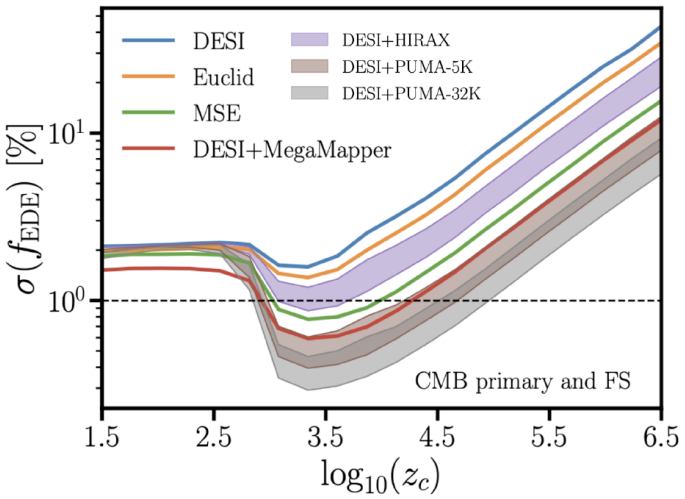

Figure 5-4. *Projected sensitivity of current and next-generation high redshift cosmic surveys to the fractional dark energy density relative to closure density near the CMB recombination epoch. The signal of early cosmic acceleration is an alteration to the growth of structure as measured as measured via the matter power spectrum of the large scale structure. In particular, these probes will test models of early dark energy designed to explain the "Hubble tension," a discrepancy between high redshift CMB measurements and low redshift optical survey measurements of the Hubble expansion rate which has increased in statistical significance. From the CF4 report [4].*

points of synergy with CMB-S4 and will help the community to build a unified picture of the physics underlying both the early and late-time eras of cosmic acceleration.

A major strength of Spec-S5, in any of its proposed implementations, will be its ability to advance our understanding on multiple science fronts simultaneously, while also enhancing the science outcomes from other experiments in the CF portfolio. Cross-correlation measurements that combine Spec-S5 data with other surveys can be used to improve photometric redshifts for LSST as well as to unlock additional cosmological information (generally with reduced systematic uncertainties). A Spec-S5 could also play an important role in obtaining training redshifts for LSST photo-z's, improving cosmological constraints from this key dataset. Construction of the instrument for a Spec-S5 facility in collaboration with other partners could build upon HEP strengths and experience with DESI. Realizing Spec-S5 in any of the funding scenarios that P5 might consider would play a key role in advancing the scientific goals of the CF community.

5.2.3 Gravitational Waves

The emergence of gravitational wave observatories (GWO) sensitive enough to detect sources at cosmic distances has revolutionized humanity's view of the universe. The HEP community, and the Cosmic Frontier sub-community in particular has been quick in realizing the implications of this new development and has been working towards incorporating GWO projects in our portfolio. Gravitational-wave standard sirens (merging compact object binary systems) allow measurement of the luminosity distance of the source and, together with redshift measurements, can be used to measure H_0 via the distance-redshift relation. Measurement of the Hubble parameter using standard sirens does not require a cosmic distance ladder and is model-independent: the absolute luminosity distance is directly calibrated by the theory of general

relativity. Aiming to develop standard sirens into fully-fledged probes of dark energy, the DES collaboration launched a search and discovery program for the electromagnetic (EM) counterparts of events detected by the current GWO projects LIGO/Virgo. DES participated in the first multi-messenger discovery, of the binary neutron star merger GW170817, and contributed to the first standard siren-based measurements of H_0. Approximately fifty additional multi-messenger binary neutron star observations would be needed to reach the required precision to weigh in the Hubble tension debate [13]. The community is currently planning upgrades to the existing GWO network as well as a next-generation GWO network. One proposed next-generation project led by the US with participation from international partners is known as Cosmic Explorer. The CF community plans to use standard sirens from a Cosmic Explorer-like GWO as a powerful sample of independent distance indicators going all the way up to $z = 10$. Combined with deep optical-to-near-infrared Stage IV and Stage V EM observatories, we can reach the required precision for Stage VI dark energy science. The potential impact of adding GWO data to our dark energy science program is seen in the top panel of Figure 5-1 based on forecasts performed by the community [4, 5, 13, 14].

Gravitational waves can probe dark energy and cosmic acceleration throughout the entire history of the universe with an observable that is novel and largely independent from the traditional observables employed thus far in the field. The next-generation GWO network will also have access to the binary black hole population when the universe was still in its infancy, to the equation of state of matter at neutron star cores at supranuclear densities and quark deconfinement phase transitions in hot merger remnants, and the ability to measure the properties of dark energy and dark matter, to stochastic gravitational-waves from early-universe phase transitions, and to the highly warped space-time in the strong-field and high-velocity limit of general relativity.

The CF community plans to incorporate GWO into its portfolio of tools for discovery with a long term strategic vision. We will pursue EM counterparts of events detected by the growing GWO network while launching new pathfinder R&D efforts to enable the HEP community to participate in the next-generation GWO project in a leading role. The sensitivity goals for new detectors, roughly 10 times better than the planned LIGO upgrade, require significantly larger facilities and a number of technological upgrades. Both are challenging requirements that the HEP community is well-equipped to meet.

This is likely a once-in-a-century opportunity for the HEP community to make new breakthroughs in an entirely new class of experiments; we can take advantage of this new opportunity to advance on our scientific drivers at a much faster pace than previously anticipated.

5.2.4 Experimental Program & Facilities: Cross-Experiment Strategic Plan

In light of the opportunities for new breakthroughs in dark energy and cosmic acceleration over the next decades, the CF community has converged on a strategic plan with both near-term and longer-term action items, built upon a set of highly complementary projects/facilities and research initiatives. The top panel in Figure 5-1 summarizes how cosmic surveys will advance over Stages IV-VI using a key statistic: the maximum redshift where we can measure the contribution of dark energy to the total mass-energy density of the universe with percent-level precision. We set the threshold for discovery at $z = 8$, which will allow us to rigorously test the cosmological constant hypothesis far beyond the dark energy-dominated era of the universe. Stage III has achieved this at $z < 0.7$, and Stage IV should reach this goal for $z \lesssim 1.5$. In contrast Stage V and VI experiments should extend our reach to $z \sim 5$ and $z \lesssim$ 8-10, respectively. These measurements will allow us to definitively test whether simple cosmological constant or time-varying w_0/w_a models are sufficient descriptions of cosmic acceleration, or if instead more exotic explanations with more complicated time evolution (such as those invoked to explain existing tensions, such as the models illustrated

in Figure 5-3) will be needed. In either scenario, Stages V and VI will lead to a breakthrough comparable to, if not surpassing, the discovery of dark energy itself.

Figures 5-3 and 5-4 show projections for the sensitivity of example proposed Stage V and Stage VI surveys relative to current Stage IV surveys for two key parameters: the energy density of dark energy ($\Omega_{\rm DE}$), and the contribution of early dark energy to the overall cosmological model ($f_{\rm EDE}$). The program devised by the CF community will enable us to test a wide variety of dark energy models that have been proposed to explain the observed tensions in H_0 and S_8.

We summarize here the expected progression of projects and the key areas of support needed to address the questions of cosmic acceleration in both the modern and inflationary eras as described in the CF4 [4], CF5 [5], and CF6 [6] reports (noting that there is no significance to the ordering of items):

Near-future efforts: In the near term, it will be important to complete the Stage IV projects and fund the science efforts needed to take advantage of these powerful new facilities, including obtaining complementary data which will make them more powerful. Key needs to ensure the success of this program are to:

- Build and operate CMB-S4.
- Begin operation of Rubin LSST.
- Continue operation of DESI (via a new DESI-II program) to constrain dark energy in new domains and as a step towards a Stage V spectroscopic facility (Spec-S5).
- Fund science analyses of the Stage IV datasets.
- Establish funding mechanisms for small and medium scale projects to follow up transients discovered by LSST and standard sirens discovered by gravitational wave observatory (GWO) facilities, as well as to enable photometric redshift training spectroscopy for LSST.

Longer-term efforts: In order to enable longer-term progress, it will be vital to establish a flagship Spec-S5 program, as well as to explore new opportunities which can enable other Stage V and even Stage VI experiments. Key needs for this progress are to:

- Build and operate Spec-S5.
- Support R&D and pathfinder studies for a next-generation GWO.
- Support R&D and pathfinder studies for a next-generation CMB experiment (at the Stage V or VI level).
- Support R&D and small projects to develop technologies and methods that can enable a future surveys (e.g., LIM and CMB-S5) and new precision probes of cosmology (e.g., redshift drift measurements).
- Support operations of Rubin Observatory beyond the initially planned 10 year LSST survey; the best future use of this facility should be evaluated later this decade after the first LSST analyses have been done.

Taking advantage of complementary experiments: The experiments in our program will probe dark energy physics in a variety of different ways, enabling cross-checks for and control of systematic uncertainties to obtain robust and rigorous results. For example, standard siren measurements based on sources from gravitational wave observatories will be subject to very different systematics from observables such as

galaxy clustering or supernovae that have been commonly employed in precision cosmology studies to date. Furthermore, different experiments provide complementary information about the universe that yields more powerful constraints on cosmology when analyzed in combination.

However, such combined analyses present more challenges (particularly organizationally) than those which only involve one science collaboration. Key needs to ensure the success of multi-experiment analyses are to:

- Create funding streams and support for cross-survey analyses.
- Develop and support coordination between large facilities for optimized design, timely execution, and joint analyses.
- Create data archive centers for long term storage where data from cosmological surveys is replicated, continuously available, and easily accessible with software and computing resources for developing joint constraints on dark energy, inflation and dark matter.
- Create and support development of a diverse set of simulated data sets that could be used in joint analyses. Support should include common access to data and super-computing resources.

The CF strategy for medium and large cosmic survey facilities is designed to take advantage of the interconnected nature of the science questions we aim to approach. The same facilities which can provide compelling tests of the nature of cosmic acceleration can also probe the physics of inflation, neutrino masses, dark matter, and dark radiation, as described in other sections of this report. This is illustrated in Figure 5-5, taken from the CF6 report [6], which depicts the different areas of cosmic frontier science addressed by wide-field spectroscopic facilities (such as Spec-S5), CMB experiments (such as CMB-S4), line intensity mapping (which may play a key role in Stage VI), and gravitational wave observatories.

By incorporating both near-term and long-term projects at a range of scales, this experimental program should ensure that high-impact science results are continuously produced, avoiding lengthy gaps during project construction. In sum, the ecosystem of cosmic surveys proposed by the community should efficiently address many of the greatest scientific questions of our time. Accomplishing this program in its entirety will ensure that the HEP community will continue its path of leadership in studies of the accelerating universe.

5.3 Inflation

There is strong evidence that the universe went through an extended period of accelerated expansion during its earliest moments. The observed homogeneity and isotropy of the universe can be explained by 60 e-foldings of expansion of a much smaller, causally connected volume. Furthermore, the fluctuations in the hot plasma that ultimately become the large scale structure (LSS) of the matter distribution are elegantly explained as originating from quantum fluctuations sourced throughout inflation and stretched to enormous distances by the exponential expansion. Also, during this epoch, the universe effectively conducted the most extreme high energy physics experiment imaginable, and remnants of the dynamics of primordial ultra-high-energy collisions may remain imprinted as patterns in the density fluctuations of the resulting matter distribution.

During the inflationary epoch, cosmic acceleration is believed to be sourced by a non-vanishing vacuum energy density of a scalar inflaton field which, analogously to the Higgs field of the electroweak sector, is rolling to the minimum of its potential energy function in the midst of a cosmological phase transition. At the end of this phase transition, the decay of the inflaton field "reheats" the universe, releasing its potential energy to repopulate empty space with matter and radiation that become the photons, baryons, and dark

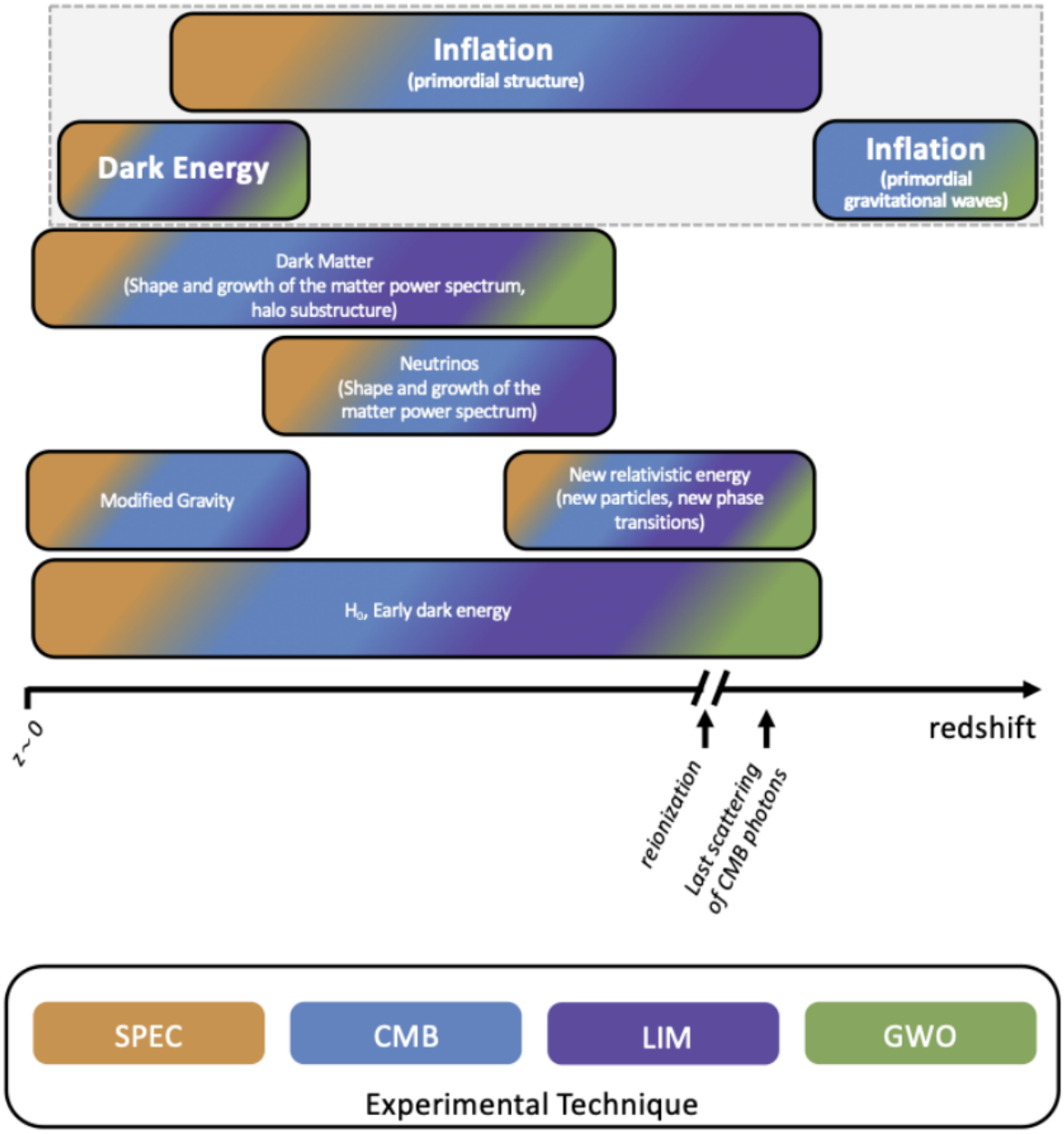

Figure 5-5. *A high-level summary of the key scientific opportunities. The horizontal extent of each box corresponds to the redshift-range of the tracer, while the coloring indicates the experimental technique used to measure the signal. The dashed grey box emphasizes dark energy and inflationary probes. From the CF6 report [6].*

matter that are observed today. Quantum fluctuations of the inflaton field therefore produce a primordial spectrum of energy density fluctuations that source the large-scale structure of the spatial distribution of dark matter and ultimately the corresponding distribution of galaxies formed by the infall of baryons into the

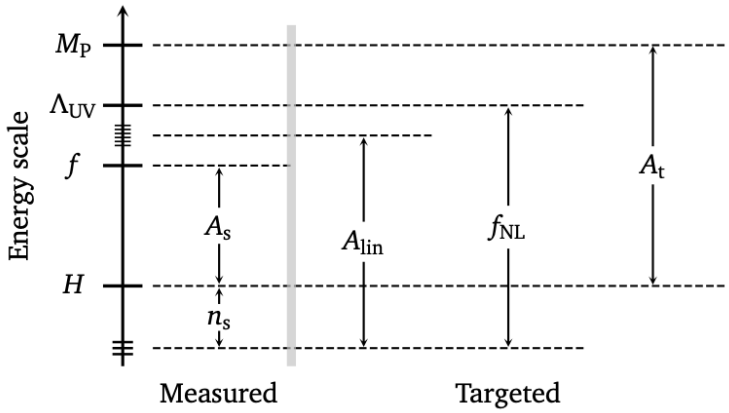

Figure 5-6. *Cartoon of the various energy scales probed by studies of cosmic inflation. The scalar amplitude A_s and spectral index n_s of the density fluctuations have already been well-measured via the temperature power spectrum of the CMB. Small features of amplitude $A_{\rm lin}$ in this spectrum may indicate new BSM resonances in inflaton-inflaton scattering. Primordial non-Gaussianities with amplitude $f_{\rm NL}$ measured via 3-point correlation functions can be used to discern inflaton scattering dynamics, e.g. soft scatters versus high-p_t event topologies, at even higher energy scales $\Lambda_{\rm UV}$ and also distinguish between models with different particle content. Finally, the tensor amplitude A_t of the spectrum of gravitational waves emitted by the inflationary horizon can be measured via its imprint on the B-mode CMB polarization patterns and will provide an absolute determination of the Hubble scale H of inflation relative to the Planck scale $M_{\rm P}$. Interestingly, the high energy scales accessible by CMB measurements coincide with the scale of grand unification. From Ref. [15].*

dark matter gravitational potential wells. The spectrum of these fluctuations is measured statistically via the spatial two-point correlation function of fluctuations in the observed CMB temperature and in the LSS using angle and redshift-resolved measurements of the matter distribution. A key prediction of a nearly scale-invariant power spectrum produced during the period of uniform exponential expansion has been verified by CMB data. As described below, current and future experiments are now focused on determining the energy scale of inflation by measuring B-mode polarization patterns in the CMB, determining the dynamics and active degrees of freedom in the inflation sector by measuring 3-point correlation functions, and searching for resonances in the various power spectra due to new BSM scattering processes using the inflaton waves as the ultra-high-energy beam [15]. The various energy scales accessed by these various probes are summarized in figure 5-6.

Thus far, measurements of the CMB have provided the most powerful probes of inflation. Polarization-sensitive experiments like CMB-S4 offer unique windows on the B-mode patterns, which reveal the absolute energy scale of inflation and will continue to provide precision measurements of the other key observables. Upcoming cosmic surveys including DESI and an envisioned Spec-S5 project will provide much larger datasets, using precise redshift determinations to map the matter distribution in all 3 dimensions instead of being constrained to a single 2-dimensional slice at the surface of last scattering. A new technique of line intensity mapping of the 3-d distributions of neutral hydrogen or other gas will possibly access the largest range of redshifts to provide the highest statistics measurements of the large scale structure.

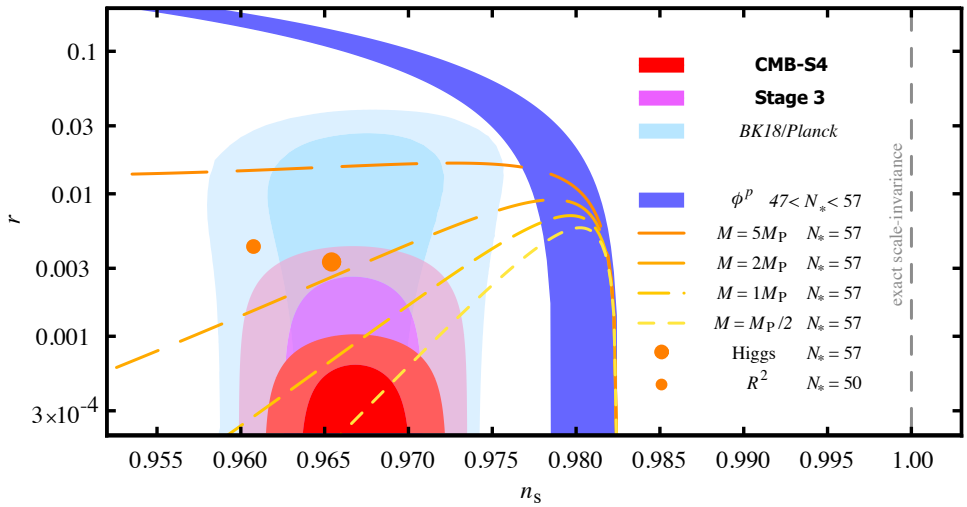

Figure 5-7. *The tensor-to-scalar ratio r plotted vs. the matter power spectral index n_s. r is observed from B-mode polarization patterns in the CMB sky, and is a measure of the absolute energy scale of cosmic inflation in the 10^{16} GeV range. The light blue region represents current constraints, the purple region the projected constraints from ongoing experiments including the South Pole Observatory and the Simons Observatory, and the red region the targeted sensitivity of CMB-S4. Dots and lines represent various models of inflation which will be tested. Adapted from Ref. [16].*

5.3.1 The Energy Scale of Inflation via CMB B-mode measurements

In many of the simplest models of inflation, a stochastic background of primordial gravitational waves is emitted by quantum fluctuations at the inflationary horizon. The amplitude of this spectrum directly provides the ratio of the scale of inflation to the Planck scale. Propagation of these gravitational waves through the primordial plasma creates characteristic B-mode polarization patterns which constitute a primary science target for CMB experiments. The sensitivity of CMB-S4 to the ratio r of tensor power in B-modes to scalar power observed in the temperature fluctuation power spectrum is shown in Figure 5-7, overlaid on predictions from some of the simplest models of the inflaton sector. For example, a detection of $r \gtrsim 0.01$ by stage 3 experiments such as the South Pole Observatory or the Simons Observatory would provide evidence for an approximate shift symmetry in quantum gravity while a detection of $r \gtrsim 0.001$ by CMB-S4 would be expected in the simplest, natural models of high scale inflation. A positive detection would identify a new fundamental energy scale of nature, possibly coincident with the putative scale of grand unification, and also provide the first evidence for the quantum nature of gravitational waves. Conversely, a non-detection would point towards more complicated models of inflation, possibly occurring at lower energy scales.

The B-mode power of 10's of nK being probed by CMB-S4 is orders of magnitude below the scalar temperature anisotropy power, and so the signal is expected to be extremely faint. A key challenge is to accurately measure, model, and subtract polarized foregrounds due to thermal dust and synchotron emission within our Galaxy, as well as "lensing B-modes" produced by weak gravitational lensing of the CMB. Given the tremendous increase in volume and complexity of the upcoming datasets, continued development in the modeling and simulation of these foregrounds and of lensing, in computational analysis techniques, and in theoretical work will be necessary to fully realize the science potential of this project.

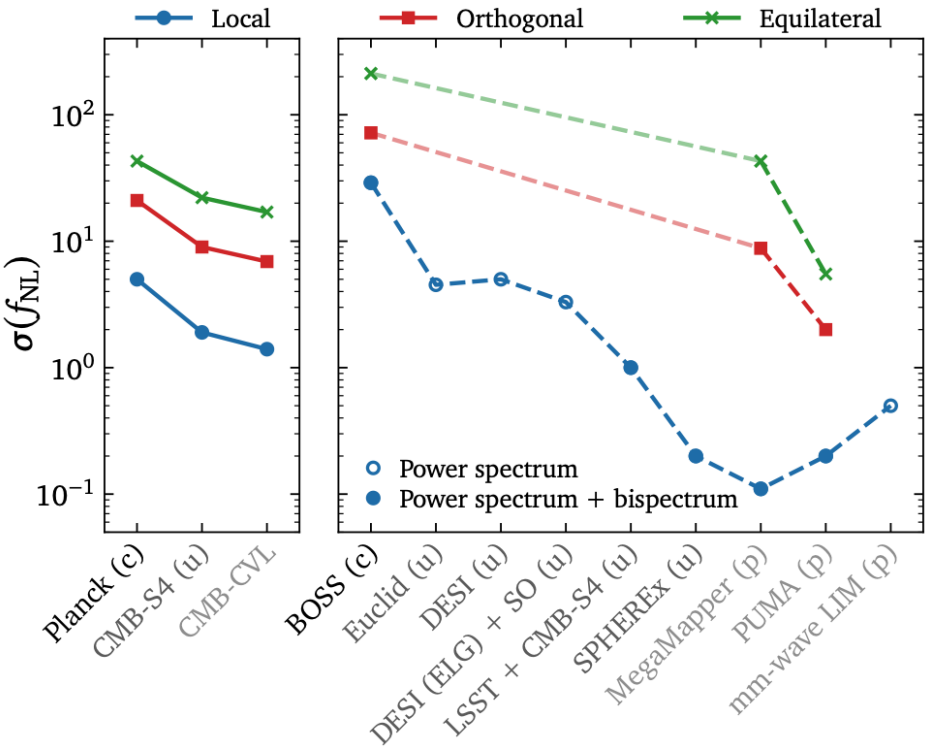

Figure 5-8. *Resolution on the amplitude f_{NL} of the power bispectrum of the 3-point correlation function of matter density fluctuations for existing and planned future cosmic survey projects. Three representative shapes (local, orthogonal, equilateral) are used for the 3-point function to measure scattering dynamics and field content in different event topologies. The sensitivity of CMB probes (left panel) to new dynamics in the inflaton sector should greatly improve with the advent of CMB-S4. Planned future Stage V spectroscopic surveys (such as MegaMapper, as shown in the right panel) will provide larger data sets by incorporating redshift information to reconstruct the full, 3-dimensional matter distribution. From Ref. [15].*

5.3.2 Primordial Non-Gaussianities: Reconstructing the Physics of Inflation

Current observations of the primordial density fluctuations are consistent with the Gaussian white noise statistics of a non-interacting gas of inflatons, freely propagating after being generated by quantum fluctuations at the horizon. However, deviations from Gaussianity are necessarily present in even the simplest models of inflation. For example, a generic inflaton potential energy function will contain higher-order terms describing inflaton self-interactions, and inflaton self scattering events would redistribute the spectral power. Detecting primordial non-Gaussianities (PNG) in the inflaton gas as mirrored in the resulting density fluctuations would provide valuable information about the dynamics at play during the inflationary epoch.

It is helpful to think of the inflationary epoch as a collider experiment operated at extremely high energy densities. Low-mass particles produced during inflation propagate long distances and are primarily responsible for the fluctuations in energy density produced after they decay and reheat the universe. The scalar power spectrum measured in the CMB then characterizes the energy distribution and intensity of the particle beam. To measure scattering and therefore interactions, it is easiest to probe higher-point statistics whose correlation functions encode the scattering dynamics as well as information about the different particle species participating in the interactions. For example, just as the topology of hadronic jets produced in a

collider experiment provide information about the underlying event, measurements of the 3-point correlation function of density fluctuations can provide statistical information about the fundamental interactions and microphysics within the inflaton sector as well as those of other BSM physics at energy scales accessible to the inflaton beam. The 3-point functions measured on triangles formed at each distance scale probe scattering events at different center-of-mass energies, and the lengths of the triangle sides encode the kinematics of the events. The collection of such events in the sky forms a high-statistics data set of independent scattering events at each energy. Surveys which incorporate spectroscopic information can characterize a greater number of different modes on scales that evolve linearly, $N_{\rm modes}$, especially at higher redshifts where they encompass more volume.

Primordial non-Gaussianity is typically parameterized by the strength of the interaction and by the momentum dependence or shape or topology of the signal. Depending on how strong correlations are between short and long distances, different information can be inferred about the dynamical processes responsible for the correlations. For example, self-interactions between inflaton perturbations generate correlations among modes of comparable wavelength and therefore the signal tends to peak around an equilateral triangle configuration. When there are strong correlations between short and long wavelength modes, a messenger particle is responsible for the long-range interaction. The resulting signal is called "local non-Gaussianity," and is a robust probe of new physics beyond the inflaton fluctuation and its self-interactions. Said differently, equilateral non-Gaussianity probes interactions of the inflaton with itself and local non-Gaussianity probes light extra mediator fields (and also potentially can distinguish between single field and multi-field inflation models). While this is a useful general classification, there are many interesting scenarios in between these two extreme cases.

The primordial non-Gaussianity signal is generally characterized by an amplitude $f_{\rm NL}$; signatures of nonzero $f_{\rm NL}$ can manifest in both the observed power spectrum of density fluctuations as well as in their bispectrum — i.e., the Fourier transform of the 3-point function calculated for various triangle topologies. Current and projected sensitivity to $f_{\rm NL}$ is shown in figure 5-8. The upcoming CMB-S4 experiment will provide much greater sensitivity to interesting models. For example, for local non-Gaussianity, models with models with $f_{\rm NL}^{\rm local} > 1$, which would produce signals detectable by CMB-S4, point to the existence of extra low-mass species active during or after inflation which are emitted colinearly in the primordial scattering events. This measurement thus constitutes a powerful search for new BSM particles over a broad range of masses up to the beam energy given by the inflationary Hubble scale H. For equilateral and orthogonal non-Gaussianity, models with $f_{\rm NL} > 1$ tend to favor scenarios with a strong breaking of boost symmetries of the inflationary background (or small sound speed of the scalar perturbations).

Future planned optical spectroscopic surveys will provide even greater sensitivity by incorporating redshift information to measure the full 3-dimensional matter distribution. By measuring this distribution over the larger volumes available at higher redshifts, future datasets will increase the scattering event statistics by a factor of 10-100 relative to the $N_{\rm modes}$ achieved by DESI, an improvement factor measured by the "primordial figure-of-merit." For example, the first factor of 10 would come from a Stage V Spectroscopic Facility targeting redshift $2 < z < 5$ galaxies using the LSST dataset. The statistics could be improved by a factor of 100 using a relatively inexpensive line intensity mapping (LIM) technique to probe the same physics and by using 21 cm observations to map the large scale distributions of neutral hydrogen in the universe via 21 cm emissions. The long term goal is to explore the vast pristine volume before the first stars ignited. LuSEE-Night pathfinder is focusing on the Dark Ages monopole and will make the first steps in understanding systematics to determine whether the full statistical power can be achieved.

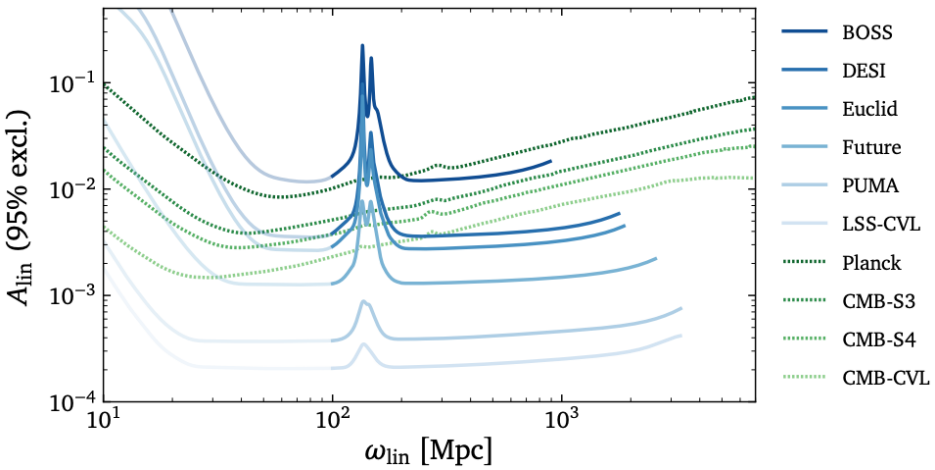

Figure 5-9. *Current and projected sensitivity to small spectral features in the matter power spectrum for CMB and LSS probes. Sensitivity limits on $A_{\rm lin}$, the fractional amplitude of the feature to the amplitude of the nearly scale-independent power spectrum, is plotted vs. the wavelength of the perturbation. Searches for features in the matter power spectrum can also reveal new BSM dynamics at energy scales accessible at inflaton scattering energies. For example, new resonances at these ultra high energy scales may be revealed by bump-hunting searches. More generally, spectral features which break scale invariance indicate new BSM dynamics. Again, while CMB data currently provide the greatest sensitivity, a Stage V spectroscopic survey (exemplified by the 'future' limit depicted here) would provide more sensitive constraints at high $\omega_{\rm lin}$ by accessing 3-dimensional information over a large volume. From Ref. [15].*

5.3.3 Spectral Features: Uncovering New Dynamics in the Primordial Universe

While the observed flat spectral index $n_s \simeq 0.97$ of the linear power spectrum of density fluctuations is consistent with a mild time dependence of the inflationary perturbations due to the small slope of slow-roll inflation models, more dramatic deviations from scale invariance can arise from (i) sharp or oscillatory features in the potential, (ii) power-law changes to the power spectrum on small scales, or (iii) new BSM resonances accessible at the energies of the inflaton waves. Oscillatory features arise naturally from a variety of microscopic models of inflation. This periodic potential would then create a spectrum of harmonics on top of the predominant power law distribution.

To date, cosmological data has constrained departures from a pure power law spectrum at the 1% level; future CMB and LSS data will improve sensitivity by 1-2 orders of magnitude. Figure 5-9 shows the current and projected sensitivity to the amplitude of small spectral features for both CMB and LSS probes. Sensitivity to structure at smaller scales will utilize measurements of CMB spectral distortions and the stochastic gravitational wave background. While scale-dependent features will also be targeted by 3-point function measurements of primordial non-Gaussianities, the linear 2-point function measurements allow a cleaner separation of primordial effects from late-time nonlinearities induced by gravitational clumping on smaller scales. Note that in Figure 5-9, the projected limits labeled "Future" correspond to what we expect from a Spec-S5 project. Also shown are several CMB projections, including CMB-S4.

5.3.4 CMB-S4

CMB-S4 [17] is a Stage IV cosmic microwave background project that plans to field multiple telescopes at the South Pole and in the Atacama desert, Chile. See the Snowmass 2021 White Paper [18] for a discussion on the broader experimental context. CMB-S4 has an enormously broad science case with key science goals including searching for primordial gravitational waves through the B-mode signal in the CMB as predicted from inflation (*detecting* $r > 3 \times 10^{-3}$ *at* 5σ *or limiting* $r \leq 10^{-3}$ *at 95% confidence if* r *is very small*) and searching for the imprint of relic particles including neutrinos (*constraining* $\Delta N_{\rm eff} \leq 0.06$ *at 95% confidence*). CMB-S4 will also offer unique insights into dark energy and tests of gravity on large scales, find large samples of high-redshift galaxy clusters, elucidate the role of baryonic feedback on galaxy formation and evolution, open a window onto the transient Universe at millimeter wavelengths, and explore objects in the outer Solar System, among other investigations.

The current CMB-S4 instrument design calls for 500,000 polarization-sensitive bolometers that measure the sky at frequencies from 20–280 GHz. The superconducting detectors will be dichroic and use the feedhorn-coupled orthomode transducer architecture. They will be read out using time-domain multiplexed electronics and will be distributed between a set of telescopes at two sites: two 6-meter cross-Dragone reflecting telescopes in Chile, a 5-meter three-mirror-astigmatic reflecting telescope at the South Pole, and eighteen 0.5-meter refracting telescopes at the South Pole, grouped as triplets on six mounts, with each mount sharing a cryogenic system. This preliminary baseline design for CMB-S4 uses proven technology scaled up to much higher detector counts.

The already-established integrated project office has addressed the technical challenges of the required scale-up with a detailed design and implementation plan that includes a full work-breakdown structure. The project office also maintains a register of risks and a detailed cost estimation plan. The preliminary, technology-limited project schedule contains nearly nine thousand milestones and catalogs the dependent relationships between them. The CMB-S4 project is moving forward and is ready to advance our compelling scientific program immediately.

5.4 Dark Matter

Astronomical and cosmological observations of the gravitational influence of dark matter provide one of the strongest indications of new physics Beyond the Standard Model [19]. Ascertaining the nature of these mysterious new particles, their interactions both with Standard Model particles and with themselves, and their cosmological origin is perhaps the grand challenge of this generation. While the ambitious program to understand dark matter will require tools and techniques from across the HEP frontiers [20, 21], the Cosmic Frontier is unique in that its experiments seek to detect and measure dark matter in its natural habitat – the halo of our Galaxy, the halos of distant galaxies, and the large-scale structure of the Universe. While other frontiers may hope to discover new particles that could play the role of dark matter, only the Cosmic Frontier can establish that a given discovery is, in fact, associated with the dark matter in the Universe.

Our understanding of the landscape of dark matter theories has evolved significantly in the past several years, as theoretical exploration has better defined the boundaries of what models are consistent with observations. As of Snowmass 2013 [22], the classification of dark matter candidates was largely based on the particle physics features of the underlying models (see Figure 5-10). Since then, focus has shifted toward exploring wide ranges of the possible phenomena in an effort to understand how well existing experimental searches cover the space of possibilities, and how new experimental opportunities provide sensitivity to regions of theory-space that are not captured by the current program [23]. There is great freedom to

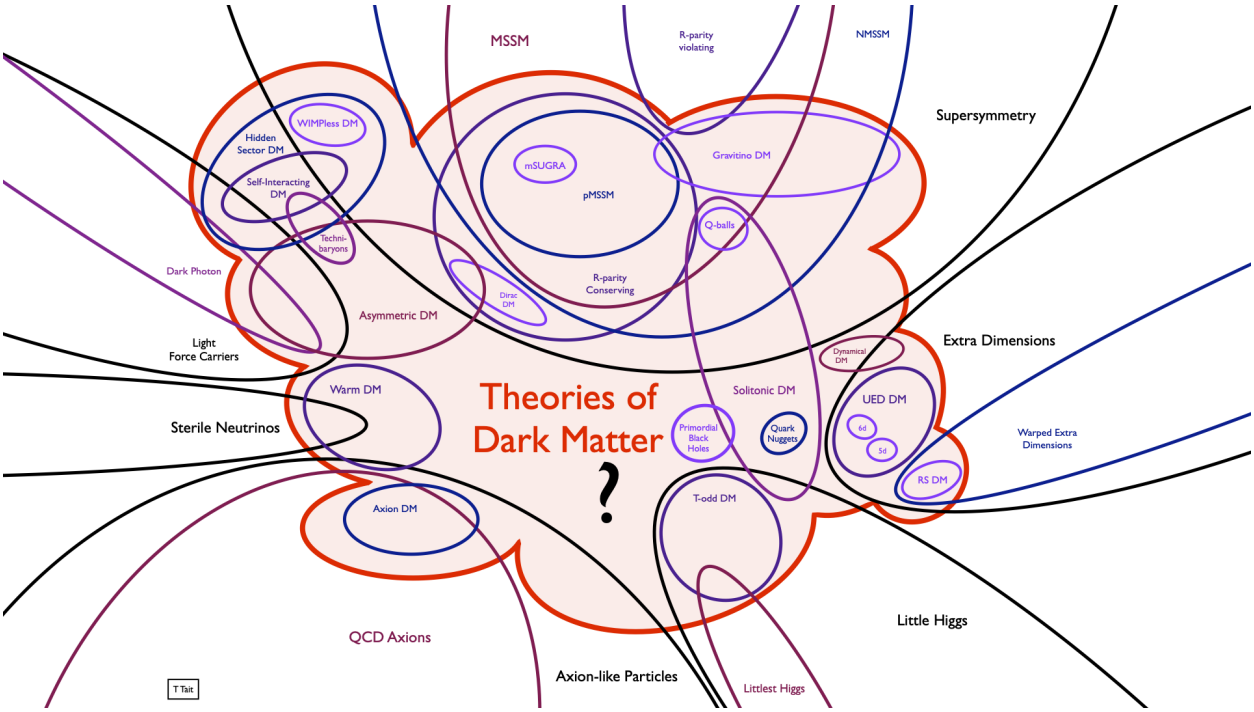

Figure 5-10. *Venn diagram of dark matter models, showing relationships between different ideas for the fundamental nature of dark matter.*

construct microphysical descriptions of dark matter, and a vast landscape of theoretical extensions of the Standard Model have been proposed. These models range from very simple extensions of the Standard Model containing a single new particle to complex dark sectors containing multiple dark matter states, composite dark matter blobs, or even towers of dark particles that could constitute several different components of dark matter simultaneously [24].

Cosmic observations currently delineate the allowed properties of dark matter. Dark matter must interact gravitationally, must be produced sufficiently non-relativistically that it clusters to form galaxies, must be sufficiently long-lived that it is present in the Universe today, and must not interact frequently with the Standard Model or it would produce signals that would have been observed. Going forward, cosmic probes offer unique opportunities to learn about the properties of dark matter via the influence that it exerts on ordinary matter [3]. Measurements of the distribution of dark matter, including observables such as the matter power spectrum, the characteristics of dark matter halos (e.g., the mass spectrum, distribution, and density profiles), and the abundances of compact objects have become precise enough to place bounds on fundamental properties of dark matter such as particle mass and interaction strengths with itself and with the Standard Model. Since the last Snowmass study, there have been a series of breakthroughs in modeling cosmic structure formation in novel dark matter scenarios [25]. These studies set the basis for quantifying astrophysical uncertainties and disentangling dark matter physics from baryon physics, a key step for extracting the Lagrangian parameters that describe a particular dark matter model from cosmic observations. We are at the threshold of definitively testing predictions of the cold dark matter paradigm on galactic and sub-galactic scales, and any observed deviation would revolutionize our understanding of the fundamental nature of dark matter. In many cases, cosmic measurements of dark matter can be achieved

by the same facilities that are being constructed to measure cosmic expansion assuming sufficient resources are provided [11, 26–29].

The primordial cosmic density of dark matter, which can be measured precisely from CMB data [30], sets an important backdrop for any viable theory of dark matter. Cosmic inflation typically erases any pre-existing density of dark matter, and so models must provide a physical 'origin story' to explain its presence in the Universe at the observed density. Two very plausible scenarios for how the dark matter could be produced include thermal freeze-out and misalignment production. In freeze-out, the dark matter has substantial interactions with the Standard Model which causes it to be thermally populated in the primordial plasma until freezing out of thermal equilibrium when the Hubble expansion catches up to the rate at which the dark matter and Standard Model interconvert. A dark matter mass and coupling of roughly weak scale sizes, assuming a standard cosmological history (e.g., no relevant additional physics Beyond the Standard Model aside from the dark matter itself), results in approximately the correct relic abundance to match observations [31, 32]. In misalignment production, the bosonic dark matter field is initially displaced from the minimum of its potential. Rolling to the minimum releases the initial vacuum energy as cold dark matter, whose abundance depends on the physics of the dark matter potential as well as the initial displacement of the field. While both of these mechanisms in principle connect the observed dark matter abundance to specific regions of parameter space, it is worth bearing in mind that additional new physics beyond the dark matter itself can change the expectations for early cosmology, and thus the predicted abundance as a function of the model parameters [33–39].

Experimental efforts over the past two decades have focused on experiments to search for weakly interacting massive particles and QCD axions, both of which are strongly and independently motivated by other unsolved scientific mysteries. In vanilla models of GeV-TeV mass dark matter associated with solving the electroweak gauge hierarchy problem [40], WIMPs with electroweak couplings to Standard Model particles would be naturally populated at approximately the correct density by the freeze-out mechanism described above. The QCD axion inevitably arises in PQ-type models in which the strong-CP problem (the otherwise inexplicable vanishing of the neutron electric dipole moment) is solved by promoting the strong CP-violating phase to a dynamical axion field [41]. The axion is produced via misalignment during the QCD phase transition, which causes the field roll to vanishing angle while releasing the original vacuum energy as axion dark matter. Much progress has been made in experimental searches on both fronts. Large second-generation WIMP detectors based on a variety of scattering targets, combined with indirect searches for high-energy annihilation products, have excluded Z-mediated couplings to Standard Model particles for WIMP masses up to $\sim$ TeV, and are now probing weaker couplings such as those mediated by Higgs boson exchange. Concurrently, axion experiments have finally achieved sensitivity to the predicted QCD axion coupling strengths by deploying various microwave quantum sensing technologies and have begun to slowly scan the axion mass parameter space using resonant cavity detectors. A cartoon encapsulating the current experimental situation is shown in the upper panel of Figure 5-2.

While the WIMP and the QCD axion remain perhaps the most strongly motivated dark matter candidates, the breadth of dark matter searches has expanded enormously as new tools and sensing techniques have been identified that are able to probe large swaths of previously unexplored parameter space. Many of the new techniques have been proposed by theorists identifying and studying models beyond WIMPs and QCD axions, which are compatible with all experimental and observational data and furthermore have their own well-formed dark matter origin stories.

A particularly compelling class of new models are those of portal dark matter in which a hidden dark sector interacts weakly with the Standard Model sector through low dimension Standard Model gauge singlet operators coupled to messenger particles. For example, in the case where the messenger is a vector particle connected to the Standard Model via kinetic mixing with the hypercharge field strength portal, the result is a massive dark photon whose interactions are predominantly proportional to electric charge scaled down by

the kinetic mixing parameter ε. Similarly, a dark Higgs can result from a scalar or pseudo-scalar messenger whose potential contains mixing with the Standard Model Higgs mass portal. Such theories offer natural scenarios in which the dark matter may have much smaller interactions with the Standard Model, realizing the correct freeze-out relic density for masses in the eV to GeV range, far below the weak scale. Detecting the scattering of such low-mass dark matter requires much lower threshold calorimetric detectors sensitive to recoil energies in the range μeV – keV.

A generic prediction of hidden-sector dark matter is that dark matter carries its own forces, which may produce novel signals in direct and indirect detection experiments. Such a force may also change cosmic structure formation, leading to signatures beyond the prevailing cold dark matter paradigm. For example, a dark force could operate at the most fundamental level with a range of $\mathcal{O}(10^{-12})$ cm, but it would change the dark matter distribution within $\mathcal{O}(10^{22})$ cm in galactic halos, which could be detected in cosmic observations. In particular, dark matter self-interactions provide a compelling mechanism to produce diverse dark matter distributions ranging from tiny dwarf galaxies to huge galaxy clusters as inferred from observations [42, 43], which are a long-standing puzzle in cold dark matter [44]. In the next decade, Rubin LSST will measure the dark matter distribution at unprecedented small scales and hence it will provide a unique opportunity for probing interactions in the hidden sector [3, 45]. Furthermore, detection of additional relativistic degrees of freedom by CMB-S4 would immediately imply the existence of a hidden sector [17]. Eventually, CMB-S5 could directly measure the matter power spectrum on sufficiently small scales to distinguish between e.g. CDM, self-interacting DM, and fuzzy DM, independently from baryonic tracers.

The range of possible dark matter masses spans at least 50 orders of magnitude from $\sim 10^{-22}$ to $\sim 10^{28}$ eV for individual particles with the lower end constrained by the smallest dwarf galaxies and the upper end constrained by the Planck mass. While composite baryonic matter (e.g., MACHOs) has been ruled out by measurements of the CMB and Big Bang Nucleosynthesis, exotic macroscopic compact objects, including primordial black holes, are still allowed to comprise some fraction of the dark matter up to mass scales greater than a Solar mass ($\sim 10^{57}$ GeV).

For direct detection experiments, where the dark matter interacts directly with the detector, different detection techniques are needed to match the energy scale and overall detector size to the expected energy/momentum transfer and event rates for the traversing dark matter for each regime of dark matter mass. As such, the following broad classification of types of dark matter helps to distinguish between classes of experimental techniques that can be deployed as part of the"search wide" strategy to achieve comprehensive coverage of dark matter parameter space.

- 10^{-22} eV$\lesssim m_\chi \lesssim$ 1 eV: "Ultralight" Dark Matter
- 1 eV$\lesssim m_\chi \lesssim$ 1 GeV: "Light" particle Dark Matter
- 1 GeV$\lesssim m_\chi \lesssim$ 100 TeV: "Heavy" particle Dark Matter
- $m_\chi \gtrsim$ 100 TeV: "Ultra-Heavy" Dark Matter (UHDM)

In the following sections, the status and prospects for the detection of dark matter in each category will be discussed.

5.4.1 Waves of ultralight bosonic dark matter

Provided that gravitational clumping of a single dark matter species is responsible for the formation of all galaxies and galactic substructures, the ∼kpc sizes of the dark matter halos hosting the smallest observed

dwarf galaxies imply that the mode volume is $(\Delta x)^3 = 1/(\Delta p)^3 \gtrsim (\text{kpc})^3$. Estimating the momentum dispersion from the escape velocity from this local gravitational potential well, $\Delta p = m v_{\text{escape}}$, a lower bound $m \gtrsim 10^{-22}$ eV can be derived. Dark matter with smaller masses than this "fuzzy dark matter" limit cannot be spatially localized within the volume of the smallest observed galaxies. In addition, for dark matter mass $m \leq 100$ eV, the mode occupation number must exceed unity in order for there to be enough dark matter to account for the local gravitational well that formed the dwarf galaxy. One may therefore infer from these cosmic probes that dark matter in the mass range 10^{-22} eV – 10^2 eV must be bosonic since the Pauli exclusion principle would prevent sufficient fermionic dark matter from fitting inside these small galaxies. At these low masses, the local Galactic dark matter takes the form of a gas of classical sine waves, each with large mode occupation number.

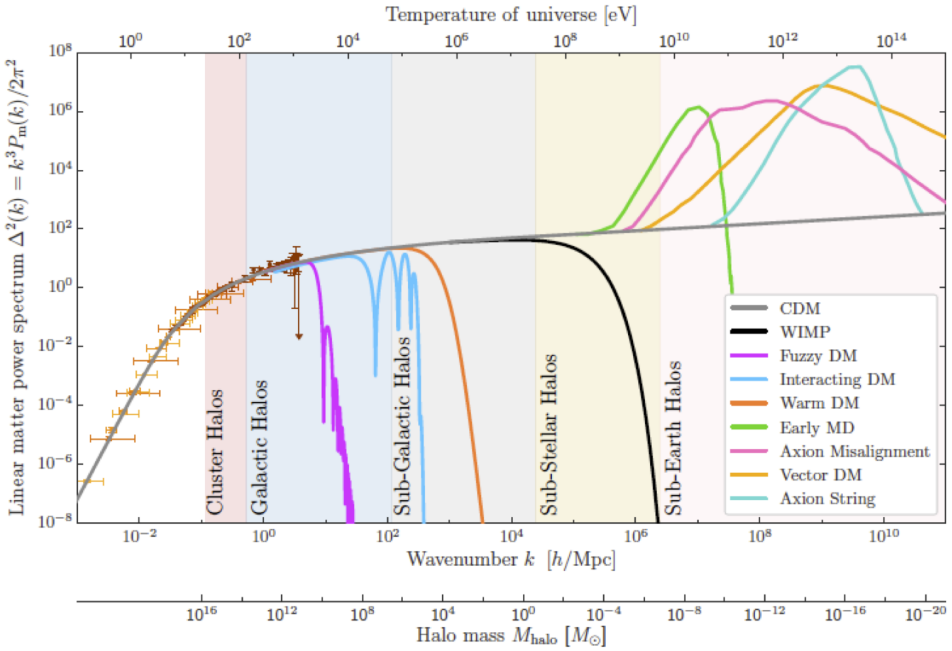

Figure 5-11. *Measurements of the distribution of dark matter provide information about its fundamental nature. The shape of the linear matter power spectrum (colored lines) and the properties of the dark matter halos that form at each scale (shaded regions) are sensitive probes of the dark matter mass and interactions. From Ref. [46].*

In the near future, cosmic surveys will gain sensitivity to even smaller dark matter halos through measurements of dwarf galaxies, stellar streams, strong lensing, and the Lyman-α forest [46]. While the canonical collisionless cold dark matter model predicts that the mass spectrum of dark matter halos extends far below the mass at which halos are known to form luminous galaxies (Figure 5-11), ultra-light bosonic dark matter that has a mass close to the fuzzy dark matter limit ($\sim 10^{-22}$ eV) or fermionic dark matter that is close to the Pauli exclusion limit (∼100 eV) would suppress the formation and density profiles of these small halos. Thus, cosmic surveys such as Rubin LSST have an opportunity to discover signatures of these models through a measured absence of small halos, or further constrain the fundamental mass scale of dark matter if small dark matter halos are observed. These are just two examples of dark matter models where fundamental dark matter properties alter the distribution of dark matter in the universe in testable ways. Similar arguments apply for a large range of specific dark matter particle models, as shown in Figure 5-11.

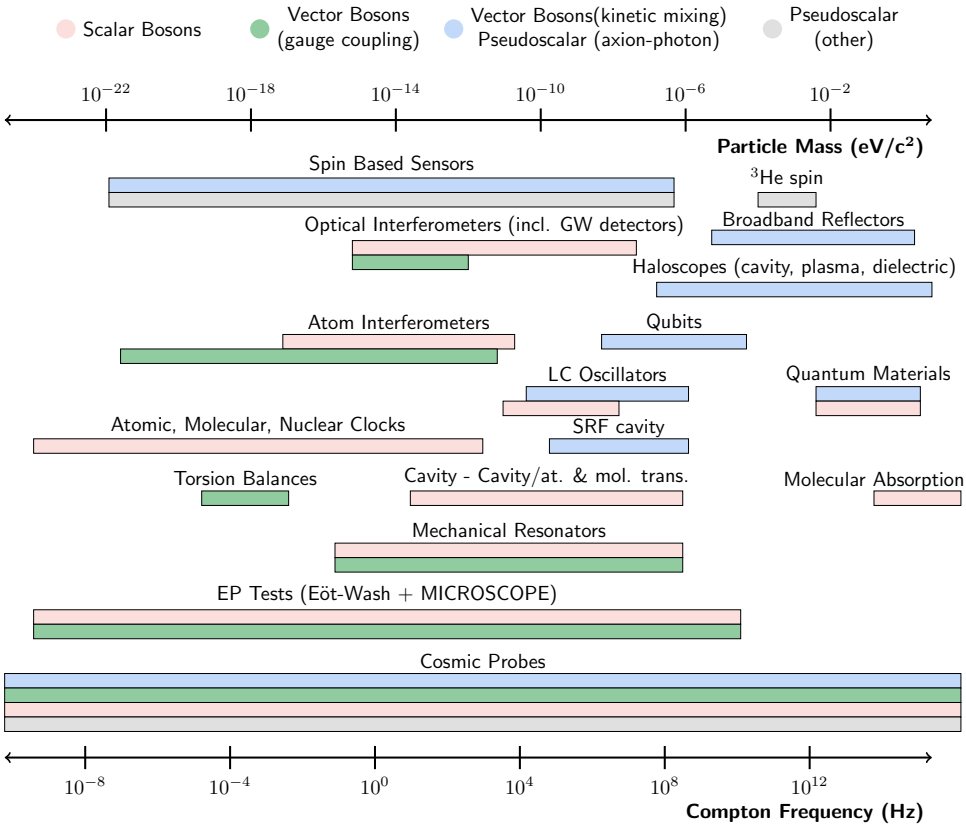

Figure 5-12. *Waves of ultra-light bosonic dark matter can be probed through a range of experimental and observational approaches including cavity experiments, quantum sensing technologies, AMO techniques, and cosmic probes. Assembled from the CF2 and CF3 reports [2, 3].*

Specialized terrestrial searches can look for modulating signals due to the oscillation of the dark matter sine wave on experimentally accessible time scales, as shown in figure 5-12. For example, the lowest mass ($m \sim 10^{-22}$ eV) wave may produce a detectable time-dependent classical force on test masses over an oscillation period of approximately one year. Another class of theories couples scalar moduli dark matter (which are ubiquitous in string theory compactifications) to the sizes of the Standard Model parameters such that the oscillation of the dark matter wave mimics a modulation of the fundamental constants. Techniques from the field of AMO physics can immediately be brought to bear on this new detection challenge, where instead of a slow drift of the fundamental constants, one optimizes the apparatus and analysis to search for narrow line, single frequency perturbations. Tools of choice include atomic clocks, atom interferometers, torsion balances, nuclear magnetic resonance, electric dipole moment experiments, and gravitational wave interferometers. For example, atomic clocks have now reached fraction frequency precision of 10^{-18} and when deployed in space missions can search for perturbations from scalar dark matter; nuclear clocks under development will have even greater reach.

While much of this work remains in the domain of AMO physics, in some cases, capabilities of the HEP labs can greatly enhance the state of the art for these techniques beyond university-scale experiments in the process of adapting them to the dark matter challenge. For example, the MAGIS pathfinder experiment will utilize an access shaft of the NuMI beamline at Fermilab to achieve a world record 100 m vertical baseline

for atom interferometry and probe dark matter interactions with period equal to the free-fall time. An upgraded km-scale interferometer is envisioned for the Sanford lab. Accelerator lab expertise in large scale experimental deployments of beam pipes, vacuum systems, etc. may also prove useful in construction and operations of future large optical interferometers.

5.4.1.1 A high priority target – the QCD axion (10^{-12} eV to 10^{-2} eV)

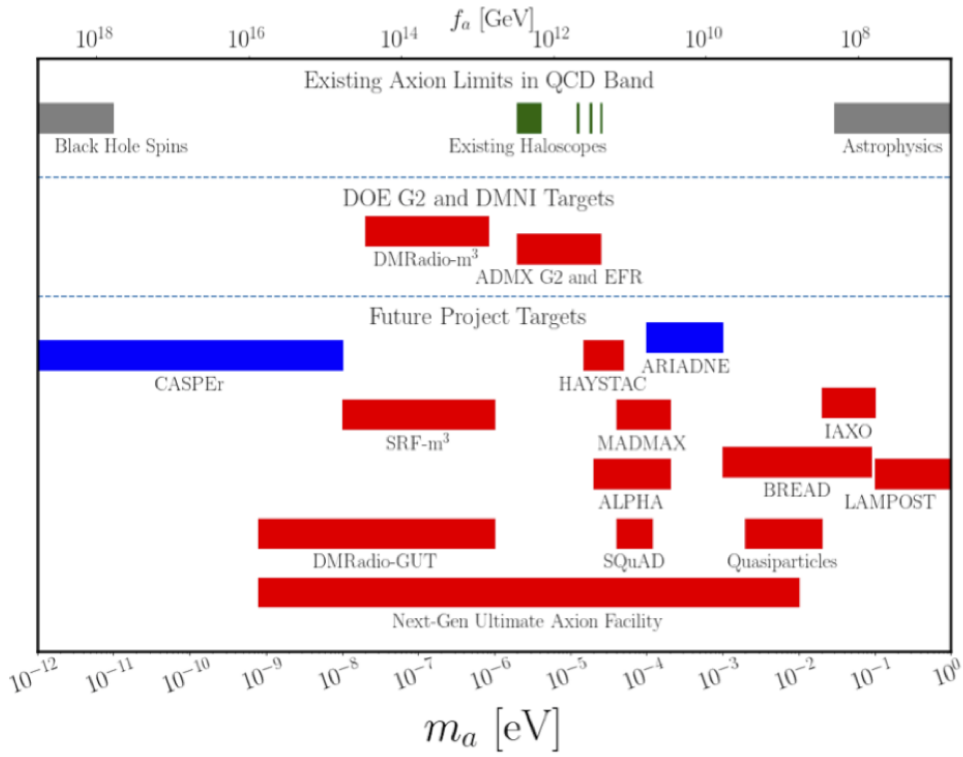

Figure 5-13. *A high priority target is the QCD axion which solves the strong CP problem as well as the origin of the dark matter. The QCD axion model makes testable predictions for the interaction strengths as a function of mass, providing useful benchmarks. This plot shows a suite of ongoing and future experiments which will test the QCD model by providing broad coverage of axion mass regions at the predicted coupling strengths to photons (red) and gluons (blue). From the CF2 report [2].*

Perhaps the most significant technological development in the field of terrestrial dark matter searches since the last Snowmass is the demonstration by ADMX and HAYSTAC of experimental sensitivity to the invisible QCD axion. The large improvement in signal/noise ratio achieved by these experiments was made possible by the deployment of new quantum sensing technologies including dilution refrigerators, quantum-limited amplifiers, and squeezed state receivers. The ability to finally begin testing the QCD axion dark matter model has renewed both experimental and theoretical interest in the field of ultralight dark matter detection with several new techniques proposed to cover nearly the entire range of allowed QCD axion dark matter masses. These experiments would concurrently provide sensitivity to large areas of model-independent parameter space for more general axion-like particles and dark photons.

The QCD axion emerges from the Peccei-Quinn (PQ) solution to the strong CP problem – the 70-year-old mystery of why the neutron has a vanishing electric dipole moment despite being made up of a Fermi-sized collection of charged quarks. The PQ model begins with a standard wine-bottle phase transition in which a global U(1) symmetry is broken at some high energy scale f_a which results in a massive Higgs mode and a massless Goldstone mode called the axion. This axion field is coupled to the gluons of QCD and thus identified with a dynamical CP-violating angle. Later, during the QCD phase transition at energy $\Lambda_{\rm QCD}$, a gluon instanton condensate slightly tilts the wine-bottle potential, causing the axion vacuum expectation value to roll to its minimum potential energy. At this true minimum, the CP-violating angle vanishes and thus zeroes out the neutron electric dipole moment. The axion gains a tiny mass $m_a = \Lambda^2_{\rm QCD}/f_a$ via this see-saw mechanism between the QCD scale and the PQ scale. Furthermore, during this vacuum relaxation process, the potential energy associated with the original CP-violating value of the misaligned vacuum axion field is released as ultracold dark matter.

The QCD axion search program is simplified in that the coupling to SM fields is proportional to the axion mass, both being proportional to $1/f_a$ as a result of the see-saw mechanism. A couple of benchmark models (KSVZ and DFSZ) with order unity coupling coefficients determine a well-defined target region which cuts a diagonal band in a more general coupling vs. mass parameter space. As shown in figure 5-13, coverage of axion parameter space can therefore be represented via a single parameter, the axion mass, with a lower bound of $\sim 10^{-12}$ eV coming from the requirement that $f_a < M_{\rm Planck}$ for the validity of the effective field theory. Cosmic probes of astrophysics in extreme environments further constrain the allowed QCD axion mass range to lie between $\sim 10^{-12}$–10^{-2} eV [47]. For example, stronger axion-nucleon couplings predicted at larger axion masses would have caused supernova 1987a to cool more quickly than observed and would lead to anomalous cooling of neutron stars [48, 49], while stronger axion-photon or axion-electron couplings would be inconsistent with stellar evolution as observed in globular clusters [50–52]. Detections of black holes with non-vanishing spins also provide constraints on axions with masses near 10^{-12} eV, since axions would populate a gravitationally bound state around black holes extracting energy and angular momentum through superradiance [53]. Future observations of extreme astrophysical environments, along with improved theoretical understanding of the Standard Model physics at play in these environments, promise to further improve our sensitivity to axion physics.

The mass parameter space can further be split into pre-inflationary and post-inflationary axion production mechanisms. The mass determines the characteristic cosmological time scale at which the initial axion potential energy in the tilted potential can be released as dark matter. Because the photon and baryon densities are redshifting away, the dark matter production time determines its relative proportion of the overall cosmological energy density. At a mass of around 10^{-5} eV, the release of an initial potential energy density of order $\Lambda^4_{\rm QCD}$ would produce the observed dark matter energy fraction. At higher masses, the energy would be released too early while the baryon density is still too high, and so the dark matter would be underproduced. However, the potential energy could be bound to networks of topological defects which would also prevent early release. At lower masses, the dark matter is released too late and would be overproduced. A solution to this overproduction problem is to posit that the initial PQ phase transition happened prior to cosmic inflation. In this case, the earth could live in an inflated patch of the universe which had a downward statistical fluctuation in initial axionic potential energy density with correspondingly less energy released as dark matter.

5.4.1.2 Joint probes of axion and cosmic inflation parameter space

The interplay of axion production histories with cosmic inflation enables complementary probes of the joint parameter space using both axion experiments and inflation experiments. For example, if a low mass axion $m_a \leq 10^{-5}$ eV is discovered in a direct detection experiment, this implies that the PQ symmetry is broken

at a high energy scale $f_a = \Lambda^2_{\rm QCD}/m_a \geq 10^{12}$ GeV. The requirement that this symmetry breaking happened prior to cosmic inflation then forces the energy scale of inflation to be quite low, $E_I \leq f_a$. Furthermore, even for very low axion masses for which $f_a \rightarrow M_{\rm Planck}$, radiation of massless axions from the inflationary horizon would produce isocurvature perturbations in the CMB which are strongly constrained by the Planck experiment. In general, the detection of a low mass axion requires that $E_I \leq 10^{14}$ GeV to avoid overproducing axion isocurvature, but then concurrently, the Hawking radiation in gravitational waves from the horizon would also produce too little tensor mode power to be observed in the CMB B-mode spectrum. CMB experiments should then instead focus on improving precision on isocurvature measurements to study this low energy scale inflation. Conversely, if inflation occurs at a high energy scale $E_I \geq 10^{16}$ GeV, the higher amplitude gravitational waves may first be measured in CMB experiments via the B-mode polarization spectrum, and low mass axions would be excluded due to overproducing isocurvature. The axion direct detection program should then focus on higher mass axions in which the PQ symmetry is broken after inflation so that no massless isocurvature modes can be produced.

5.4.1.3 Wave dark matter status and strategies for detection

In the U.S., the DOE-supported ADMX-G2 resonant cavity experiment has excluded the QCD axion in the axion frequency range 645 MHz - 1.1 GHz (2.66-4.2 μeV) at even the more pessimistic DFSZ axion-photon coupling strength, and will continue to scan upward to 2 GHz using nearly quantum limited preamplifiers in their radio receiver. The NSF-supported HAYSTAC experiment has deployed a squeezed state quantum receiver and demonstrated KSVZ coupling sensitivity in a narrow band near 4.1 GHz (17 μeV).

Two new small-scale U.S. axion experiments are being developed within the DOE's DMNI program for small projects. The first is ADMX-Extended Frequency Range (ADMX-EFR) which will increase the frequency scan rate by deploying and simultaneously operating multiple cavities within a single magnet bore, targeting higher frequencies 2-4 GHz. The other is DMRadio-m^3 which will search over a wide range of lower frequencies and lower axion masses $<$ 250 MHz (1 μeV) using a toroidal antenna incorporated into a lumped element LC circuit to couple to the axion waves. In each case, the total signal power will scale with the volume of the magnetized region which serves as the detector target for axion-photon conversion. Decisions on new starts within the DMNI program are expected to happen before the P5 report.

Meanwhile, private foundation-funded R&D continues on the CASPEr-Electric and CASPEr-Wind nuclear magnetic resonance experiments which aim to measure the dark matter-induced modulation of the nucleon electric dipole moment and the axion-nucleon spin coupling respectively. The AC effects on the spin energy levels can be resonantly detected by tuning the spin precession frequency to match the axion wave frequency and observing the resulting tilt and precession of the spin ensemble polarization vector. Both experiments are currently targeting lower frequencies/masses below 1 MHz and have a longer term goal of reaching sensitivity to the tiny signals predicted for the QCD axion. This R&D is critical as only by observing the axion in multiple, predicted detection channels can it be distinguished from more general dark matter models and proven to solve the strong-CP problem by inducing the defining nucleon electric dipole moment.

Various quantum sensing technologies are being transferred to the dark matter axion search. For example, the low frequency experiments are limited by thermal noise. In this case, single quantum mixers used can be used to transduce signal photons to higher frequency ranges where quantum limited amplification is available. The low level of quantum noise relative to thermal noise then allows the resonant search to occur at constant ratio of signal to thermal noise over many Lorentzian linewidths to recover some of the speed advantage of a broadband search – the same strategy as was used in the Weber bar technique originally used to search for gravitational waves. Another strategy is to utilize an energized superconducting RF cavity (SRF) and

use the AC magnetic field instead of a DC magnetic field to upconvert the low frequency axion wave into an RF signal photon.

At signal frequencies higher than those being probed by ADMX, the experimental challenge is that the size of the resonant cavities must shrink with increasing frequency to match the smaller wavelength of the signal photons, and so the signal power shrinks according to this rapidly decreasing target volume. While ADMX-EFR will pack many cavities into a single magnet to try to recover the lost volume, other ideas like ALPHA, the Axion Longitudinal Plasma Haloscope will try to create a large volume metallic metamaterial whose plasma frequency can be tuned into resonance with the dark matter wave. Alternatively, instead of attempting to maintain or increase the signal level, another strategy is to drastically reduce noise by using photon counting detectors which can have arbitrarily low dark count rates. The resulting noise from background count fluctuations can be far below the zero-point noise that is incurred by the currently employed frequency-resolved power readout techniques. New, ultra-low noise single microwave photon detection techniques based on superconducting qubits and on Rydberg atoms are being transferred from neighboring fields of quantum computing and AMO. The Superconducting Qubit Advantage for Dark Matter (SQuAD) prototype has demonstrated a factor of nearly 40 noise reduction relative to zero-point noise which, combined with high-Q dielectric cavities could enable QCD axion searches up to 20 GHz. R&D is also underway with the Rydberg Atoms at Yale (RAY) experiment to perform single photon counting at even higher microwave frequencies.

Finally, broadband techniques are also being developed which use large impedance mismatches at metallic or dielectric plates immersed in magnetic field to create axion to photon transition radiation. This radiation can be focused, even by the plate geometry itself, onto low noise single photon detectors. In Germany, a large R&D effort is underway to develop the MADMAX experiment which seeks to deploy a set of aligned plates to create multiple scattering targets within a large, high-field dipole magnet bore and read out signal power coherently using HEMT amplification. In the U.S., smaller-scale experiments such as BREAD and LAMPPOST are performing R&D funded by DOE-OHEP's QuantISED program to achieve high sensitivity to smaller signal levels via ultra low noise photon counting detectors such as quantum capacitance detectors, MKIDs, and SNSPDs. This new quantum photon counting technology covering 10 GHz - 100 THz may find use in various other areas of HEP outside of dark matter.

As many of these direct detection technologies are nearing maturity and are already or will be shovel-ready in the next decade, there is a key opportunity to cover most of the remaining $\sim$10 orders of magnitude in the QCD axion mass parameter space while concurrently exploring much of dark photon parameter space. The detector and sensor component of most of the experimental techniques falls firmly in the small experiment category and so a portfolio of small experiments could be strategically devised to divide and conquer the remaining axion parameter space. However, a critical path and long lead time item for most experiments is the large bore, high field magnet needed to induce the interaction between axion waves and signal photons. While resonant cavity experiments are viable in the frequency range 1-30 GHz and have been operated with commercial research solenoids or MRI magnets, the frequency scan speed has been in practice limited by the availability of magnet space. For example, if ADMX could operate two magnets instead of one, then nearly identical radios deployed in each magnet could be tasked to scan through independent frequency ranges to cover twice as much mass range in the same amount of time. Unlike most other techniques, these frequency scanning experiments enjoy linear scaling of science return with project cost which is usually dominated by magnet cost.

While the resonant experiments are constrained in size to the wavelength scale of the signal, lumped element experiments targeting lower frequencies and broadband antenna targeting higher frequencies each rely on using larger, customized magnets to intercept enough of the dark matter flow to achieve sensitivity to the QCD axion. A serious effort to comprehensively cover the many decades in allowed axion mass parameter space in finite operations time will thus require a significant investment in magnet facilities both in large,

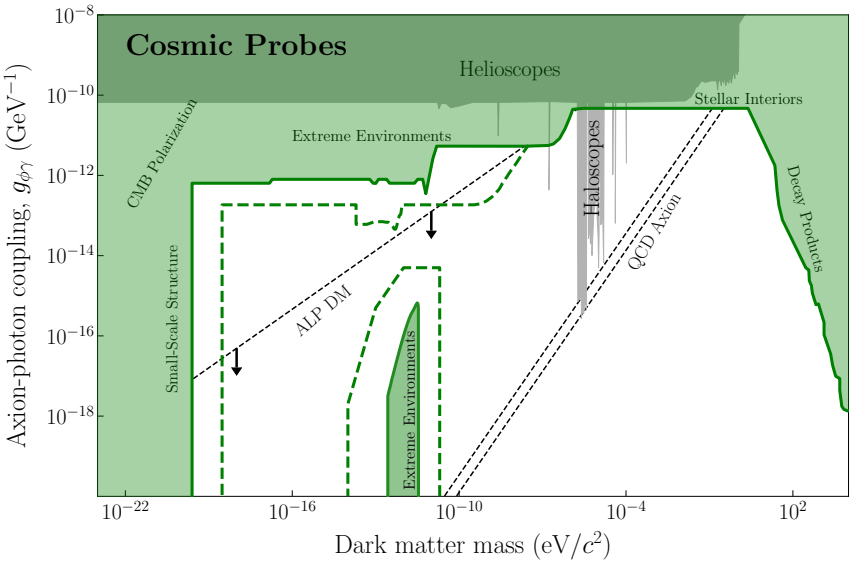

Figure 5-14. *Cosmic probes of extreme astrophysical environments combined with measurements of dark matter halos and other cosmological observations set strong constraints on the parameter space of axion-like particles (green regions). Projected improvements in sensitivity coming from future facilities and observations are indicated with a dashed green lines. Cosmic probes are sensitive well-motivated regions for the QCD axion and axion-like particles, and they are highly complementary to other experimental searches with helioscopes and haloscopes (gray regions). From the CF3 report [3].*

custom magnets for signal-limited experiments and a fleet of smaller commercial magnets for the resonant cavity experiments. Given that a Mu2e or CMS-scale solenoid may take a decade to construct, and even smaller superconducting magnets take several years to fabricate, a possible path forward is for the magnets to be planned, constructed, and operated as user facilities in which multiple experiments could be concurrently or sequentially deployed. A HEP magnet facility would focus on large bore magnets for longer term tenants, in contrast to the current portfolio of small bore, ultra high-field magnets that provided for shorter term condensed matter experiments by the NSF's National High Magnetic Field Facility.

Important constraints also arise from dark matter measurements with cosmic surveys (e.g., Rubin LSST, CMB-S4, Spec-S5) and observations of extreme astrophysical environments, which combined with advances in theory and simulations will provide sensitivity to orders of magnitude of parameter space of axions and ALPS 5-14. Fifth force searches for spin dependent forces mediated by the axion such as ARIADNE and other torsion pendulum experiments may also determine a characteristic range for the BSM Yukawa interaction and thus focus the targeted mass range for direct detection experiments. Similarly, solar searches including CAST and the proposed upgrade IAXO may determine the mass of axions escaping the hot core of the sun and provide an experimental target for the dark matter experiments.

Gravitational waves have been recently shown to be an excellent new cosmic probes of ultralight bosonic matter. For example, if the PQ phase transition is sufficiently strongly first order, then a stochastic background of gravitational waves could be created by the boiling of the vacuum during this phase transition. Measuring the spectrum of this stochastic background with LIGO or with future GW observatories would determine the energy scale of the PQ transition and then via the axion model, uniquely determine the mass of the axion dark matter. The axion direct detection program could then be focused on a narrow mass window

rather than needing multiple experiments with different technologies to cover each of the ∼10 decades the currently allowed mass window.

Searches for narrow line gravitational wave signals also constrain ultralight bosons of any type due to the prediction of the formation of gravitational atoms around spinning black holes. Just as in the hydrogen atom, particles bound to a black hole are confined to orbits of quantized angular momentum. Since bosons do not have a Pauli exclusion principle, these orbits become classically occupied with boson condensates which are created from the gravitational superradiance effect when the boson Compton wavelength is comparable to the black hole size. Transitions of bosons between different orbitals then results in narrow line gravitational wave radiation. A range of current and planned GW observatories can conduct model-independent searches for low-mass bosons from 10^{-21}–10^{-11} eV.

5.4.2 Light particle dark matter (1 eV to 1 GeV)

Above the ∼eV scale, the dark matter typically manifests as individual quanta. A priority target is the sterile neutrino, whose existence is suggested by the need to incorporate neutrino masses in the Standard Model, and which typically becomes sufficiently long-lived to play the role of dark matter at masses below around 10 keV. If sufficiently mixed with the active neutrinos, sterile neutrinos with masses below a few keV would thermalize as warm dark matter, and would suppress structure formation due to free-streaming to a degree that is inconsistent with cosmic observations. Evading this cosmological bound requires a mechanism to produce the dark matter in a very cold state, and appropriately weak coupling to the Standard Model such that it does not kinetically thermalize.

The universe itself provides an exceptional calorimeter in the form of the primordial baryon–photon plasma prior to recombination. Scattering between light dark matter and nucleons and/or electrons would transfer heat and momentum between the Standard Model and dark matter. This would have the effect of heating the dark matter and resulting in a suppression of the matter power spectrum similar to that seen in warm dark matter, which would be observable in the CMB, Lyman-α forest, and dwarf galaxies [54–58]. These cosmic probes provide access to the full range of light dark matter masses at large scattering cross sections that are inaccessible to terrestrial experiments due to shielding by the Earth's atmosphere. Expected improvements will come from current and near-future cosmic survey experiments like DESI, Rubin LSST, CMB-S4, and Spec-S5 [3, 26]. Cosmic probes are highly complementary to direct detection searches, and as illustrated in Figure 5-15 will provide sensitivity to lighter dark matter particles and higher cross sections than are accessible to direct searches.

For sub-GeV-mass dark matter, direct detection technologies generally rely on individual dark matter particles scattering or being absorbed on various target media in detectors with low energy and momentum threshold. Additional handles to distinguish the dark matter scattering signal from backgrounds are provided by the direction of the incoming dark matter, which lead to both annual and daily modulations in the signal rate. In scattering processes, the signal energy is at most the initial dark matter kinetic energy and the momentum transfer must be less than twice the initial dark matter momentum. For typical Galactic dark matter velocities of $v = 10^{-3}c$, $E_{\rm max} \approx 10^{-6} M_{\rm DM}$, and $p_{\rm max} \approx 10^{-3} M_{\rm DM}$, detectors with energy thresholds in the meV–keV range are needed to search for scattering of dark matter in the mass range keV–GeV. At these lower dark matter masses, kinematic matching for efficient billiard-ball scattering requires using lower mass nuclei, electrons, or collective modes such as phonons or magnons as scattering targets.

Noble liquid detectors have achieved signal thresholds of ~ 10 eV when detecting electrons in the ionization channel, demonstrating the lowest background rate per unit target mass in this signal energy range. Various ways of doping the target medium are being explored in order to increase scintillation and ionization yield

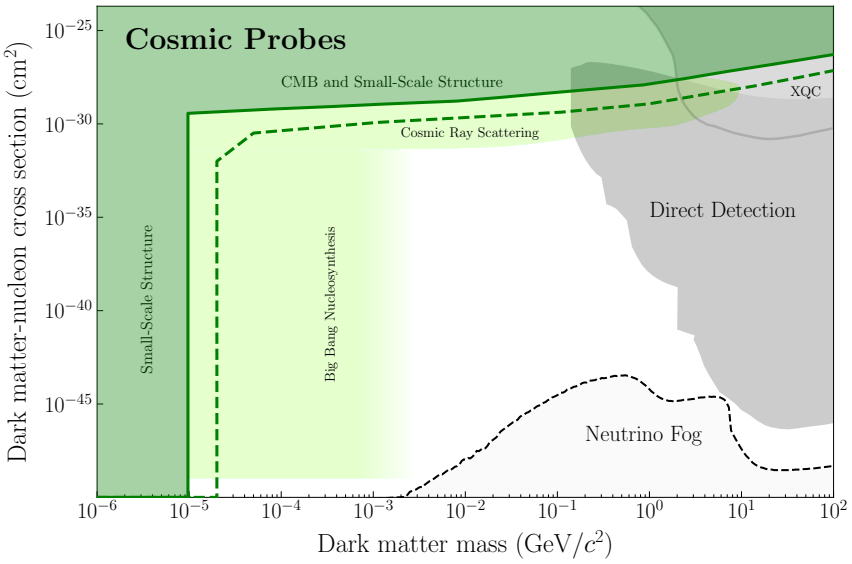

Figure 5-15. *Cosmic probes of the matter power spectrum, dark matter halos, Big Bang nucleosynthesis, and cosmic ray upscattering set strong constraints on the minimum thermal dark matter particle mass and spin-independent dark matter–nucleon scattering cross section (green regions). Projected improvements in sensitivity coming from future facilities and observations are indicated with a dashed green lines. These constraints are highly complementary to constraints from direct detection experiments (gray regions). The neutrino fog for xenon direct detection experiments is shown with dashed black line. From the CF3 report [3].*

and to improve kinematic response to lower mass particles with low-A nuclei. Odd-A nuclei also provide sensitivity to spin-dependent interactions.

Semiconductor-based detectors have a threshold near the typical band gap energies of 1 eV in the electron scattering channel, providing sensitivity to dark matter masses near 1 MeV, approximately an order of magnitude below that of the noble liquid detectors. A recent significant development has been the demonstration of sub-electron charge resolution using skipper CCDs which perform repeated, non-destructive measurements of the charge in individual pixels to average away the readout noise. The ongoing SENSEI and DAMIC-M experiments are planning a factor of 10–100 scale-up in silicon CCD target mass in a jointly proposed experiment Oscura, part of the the DOE's DMNI program. Meanwhile, semiconductor crystal detectors such as SuperCDMS HVeV and EDELWEISS are also reaching single electron sensitivity using voltage bias across the semiconductor diode to increase the single electron signal energy. The semiconductor GaAs is a bright scintillator, and single-photon-sensitive GaAs-based detectors are being developed as part of the TESSERACT program funded through DMNI, with instrumental and nuclear recoil background rejection achieved through coincident photon and phonon detection.

To further lower thresholds for the electron scattering channel, novel target materials with collective electronic excitations with meV scale bandgaps are being investigated. For example, superconducting nanowire single photon detectors can also be used to detect energy deposited from dark matter scattering events with trigger thresholds near 250 meV for localized energy deposits which quench the bias supercurrent. SPICE, also part of the TESSERACT program, is investigating low threshold dark matter detection via its electric couplings to the oscillating dipoles exhibited by optical phonon modes in polar crystals. The 10-100 meV scale bandgap of optical phonons provides both a low detection threshold and a large phase velocity for good kinematic matching to the relatively fast 300 km/s speeds of the galactic dark matter. Novel semiconductor

and semimetal compounds with meV-scale electronic bandgaps are also being developed. A key challenge is scaling up these 2-d materials to sufficiently large target masses to provide deep coverage of dark matter parameter space. Collective plasmon modes including those in new heavy fermion materials may also be better kinematically matched to low mass dark matter scattering. Directional detection of low mass dark matter may also be enabled by using bulk target materials with intrinsically anisotropic band gaps, resulting in large daily modulation in signal rates.

In the phonon channel for dark matter-nucleon scattering, the semiconductor and crystalline detectors such as CRESST, EDELWEISS, SuperCDMS, and MINER are targeting eV or sub-eV resolution by reducing the readout noise in transition edge sensors. Superfluid helium is also being investigated as part of the TESSERACT program, and is a promising material for detecting dark matter-induced nuclear recoils, combining a light, pure target with intrinsic background rejection via multiple signal channels and multi-pixel coincident readout. Beyond the NTDs and TESs traditionally used to read out microcalorimeters, new sensor technologies being explored include kinetic inductance detectors, magnetic microcalorimeters, SNSPDs, and superconducting qubits, with some of this next-generation technology being funded through various DOE quantum programs. While development of ultra-low-threshold quantum sensors may justifiably be funded through dedicated quantum programs, the deployment of these sensors and the studies of dark matter detector response including both measurements and simulations, and the characterization of new low energy backgrounds are uniquely HEP activities that could best be carried out in small, pathfinder experiments. As in the case of the axion searches described above, the DOE DMNI program currently provides funding to develop a limited number of proposed techniques. Given the variety of new sensing technologies, an opportunity exists to cover broad swaths of unexplored sub-GeV dark matter parameter space by expanding the portfolio of small experiments.

In addition to sensors designed to measure excitations of internal bulk phonon modes, a complementary approach is to monitor the center-of-mass motion of a composite object [59]. Optical or electrical readout of such mechanical sensors, in either the classical or quantum regime, offers a novel approach to detecting particle dark matter on a wide range of mass scales, including both heavy [60] and light [61] candidates. These sensors are naturally directionally dependent because they monitor changes to three-momentum of the mechanical system, and can reach energy thresholds well below the eV scale [61].

Beyond the technical capabilities of any particular detector, the distribution of deposited energies is also sensitive to the microphysics, being largely determined by nature of the mediator connecting the dark matter to the Standard Model. Heavy mediators manifest as non-renormalizable interactions which favor larger energy transfer (up to the kinematic limit), whereas light mediators enhance lower transferred energy. Figure 5-16, shows four cases of mediators, corresponding to heavy mediators with preferred coupling to electrons or nuclei, and light mediators coupled to electrons or in the form of dark photons. In each panel, existing bounds are shaded in tan, potential advances in the probed parameter space of dark matter mass versus coupling/cross section in the near term ($\sim$ 5 years) based on existing research investments are shaded green, whereas those achievable in the far term (longer time scales) are shaded blue. Each shaded region represents the combined footprint of several experiments.

Low-mass particle dark matter can be detected through its decay or annihilation into Standard Model messengers. Below a GeV, the available Standard Model channels include photons, neutrinos, electrons, muons, and the lightest hadrons. Because of poorly understood astrophysical backgrounds and confounding factors such as Galactic magnetic fields (which scramble the incident direction of charged particles), photons with energies $\gtrsim$ keV are typically considered among the most promising messengers.

Indirect searches are uniquely powerful for probing the dark matter lifetime. A compilation of constraints based on the searches for X-ray, gamma-ray, and neutrino signals across many decades of mass is shown in

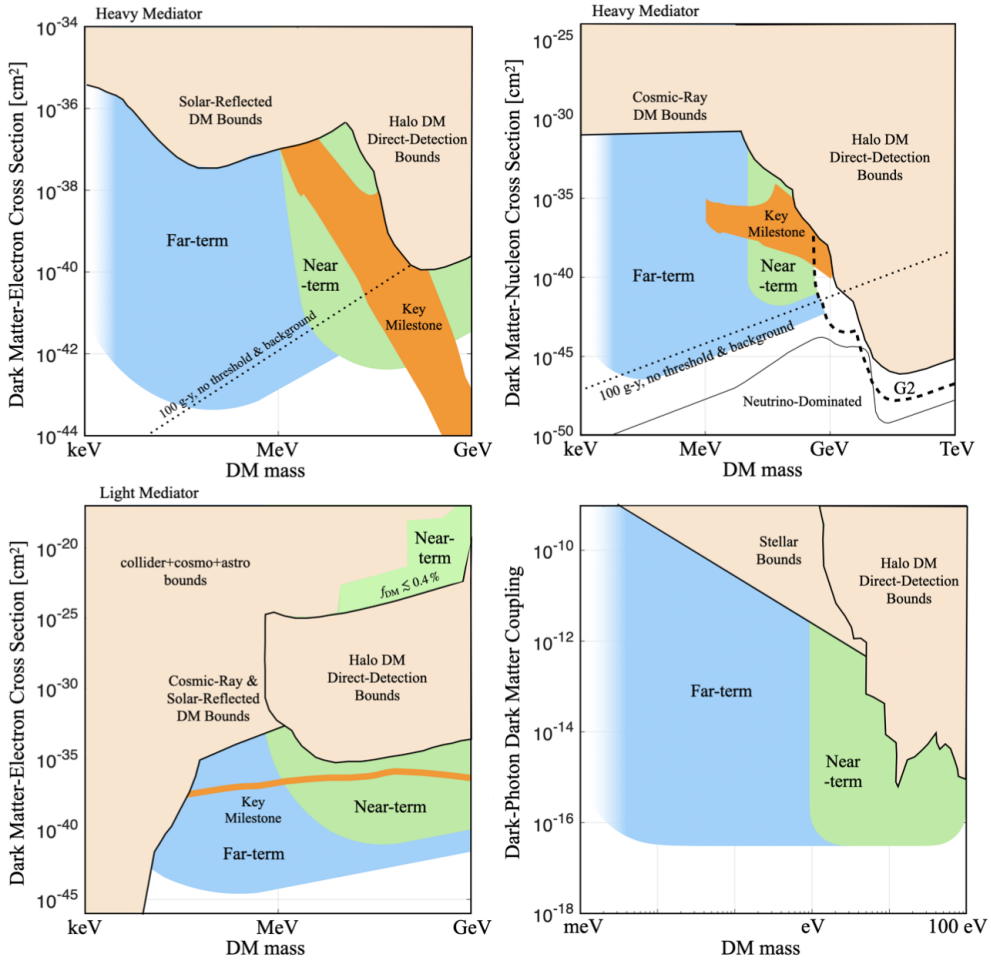

Figure 5-16. *Predicted near-term and far-term sensitivities to dark matter with mass in the range 1 eV–1 GeV through different types of mediators connecting to the Standard Model. Key milestones indicate representative target regions in which the dark matter is thermally produced for each scenario. Near-term projections are based on demonstrated sensitivities to electron recoil and nuclear recoil in the 1 eV and 10 eV range respectively. As the maximum energy deposit in scattering is the initial kinetic energy of the dark matter of order $10^{-6} M_{\rm DM}$, far term projects with lower energy thresholds will be anabled with ongoing R&D in novel target materials with band gap below the 1 eV scale of semiconductors and of chemistry. Examples include optical phonons in polar materials with band gap 10-100 meV and superconductors and other quantum materials with sub-meV gap. Concurrently, demonstration of low threshold sensor technology, including those based on quantum sensors will be required. From Ref. [62].*

Figure 5-17. It is striking that such constraints require the dark matter to live many orders of magnitude longer than the current age of the Universe.

In thermal freeze-out scenarios, indirect detection probes the same interactions that fix the dark matter abundance in the early universe. In the sub-GeV mass range, current limits already generically rule out the simple thermal freeze-out scenario for s-wave annihilation, unless the dark matter annihilation products are almost exclusively neutrinos, significantly constraining the space of viable dark matter candidates that were once in thermal contact with the Standard Model (e.g., [63]). In particular, constraints from measurements

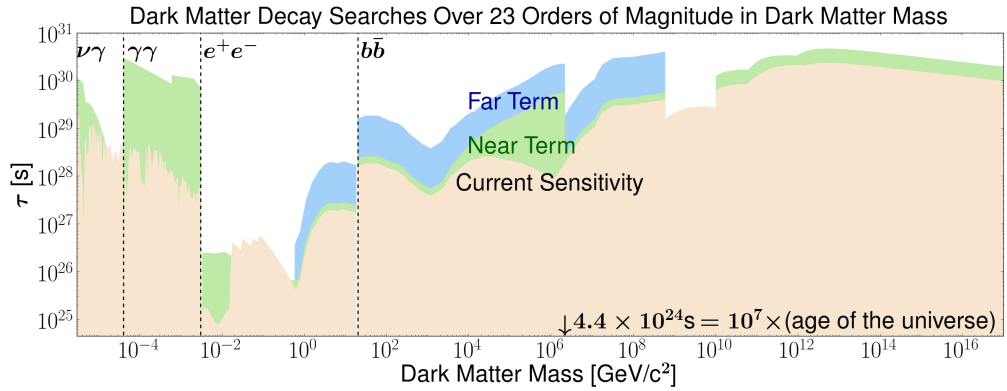

Figure 5-17. *Constraints on the lifetime of dark matter based on null searches for produced X-rays, gamma rays, and neutrinos, as well as planned improvements in the near term (green) and far term (blue). The sharp boundaries are artifacts of analysis, rather than instrumental thresholds. From the CF1 report [1].*

of the CMB [30] have a key role in establishing the viable portals by which dark sectors could communicate with the Standard Model.

At the low end of this energy range, X-ray telescopes have placed stringent constraints on sterile neutrinos, complementary to cosmic probes of warm dark matter [64]. Upcoming X-ray telescopes (XRISM [65, 66], Micro-X [67], Athena [68], HEX-P [69], Lynx [70]) will further improve constraints on decaying/annihilating light dark matter in general, and sterile neutrinos in particular; some will have sufficient energy resolution to seek to resolve DM-sourced spectral lines.

At higher energies, there is currently a sensitivity gap in the MeV–GeV gamma-ray band. The last major experiment was NASA's Imaging Compton Telescope (COMPTEL) [71], which operated from 1991–2000. Several proposed future experiments aim to address this gap: the Compton Spectrometer and Imager (COSI) [72] has a planned launch date in 2025, and will survey the gamma-ray sky at energies of 0.2–5 MeV; AMEGO-X [73] has a planned satellite launch date in the late 2020s and will probe energies from 25 keV-–1 GeV using a silicon pixel tracker, CsI calorimeter, and plastic anti-coincidence detector; and e-ASTROGAM [74] would target the 0.3 MeV–3 GeV energy range using a similar approach. Other proposals focused on the MeV band include SMILE [75–78], GRAMS [79], and GammaTPC [80], which rely on gaseous or liquid time projection chambers (TPCs), and GECCO [81] (based on a novel CdZnTe imaging calorimeter with a deployable coded aperture mask).

Investment in such experiments would enable both data-driven studies of backgrounds relevant for lower and higher energy indirect searches, as well as providing greater sensitivity to decaying and/or annihilating light dark matter in the MeV–GeV mass range. They have the potential for sufficient sensitivity to probe thermal freeze-out even when the dominant annihilation is p-wave [64, 82] (which is suppressed at non-relativistic velocities and thus challenging to observe via indirect detection), further complementing terrestrial experiments focusing on this mass range.

5.4.3 Classic WIMPs

Dark matter masses between $\sim$ GeV and hundreds of TeV populate the classic WIMP parameter space, where theories aimed at explaining the electroweak hierarchy typically reside. Such theories have been the

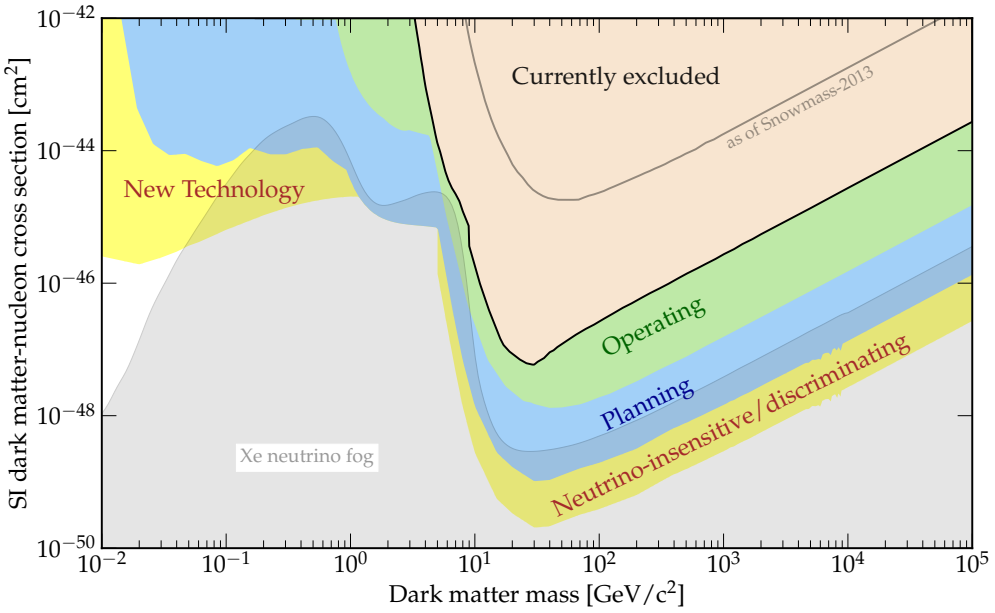

Figure 5-18. *Combined Spin-independent dark-matter nucleon scattering cross section space. Current 90% c.l. constraints are shaded beige, while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). Future experiments are shown in blue (SuperCDMS, DarkSide-20k, DarkSide-LowMass, SBC, XLZD, ARGO) and yellow (Snowball and Planned× 5). The neutrino fog for a xenon target is shaded light grey. From Ref. [97].*

subject of extensive theoretical exploration [83–88], driven both by the connection to electroweak physics as well as the fact that roughly electroweak-sized couplings naturally lead to a relic abundance close to the one required by cosmological observations through freeze-out. As a result, searches for WIMPs remain extremely well-motivated, with many interesting models inhabiting viable and testable parameter space [89, 90].

For these masses, the most efficient scattering is with nuclei, which can be described as an expansion in the dark matter velocity by terms in an effective field theory [91–94] Two classes of interactions dominate in the non-relativistic limit: spin-dependent (SD) scattering, which requires a nuclear target with non-zero spin, and spin-independent (SI) scattering, which is coherently enhanced in many models for large-A targets. Detectors employing heavy nuclei to target SI scattering have seen rapid advance in their size and control of backgrounds, achieving many decades of improved sensitivity over the past twenty years. Such experiments are now within an order of magnitude of sensitivity to the expected background neutrinos produced in the atmosphere, Sun and supernovae. This 'neutrino fog' is interesting to measure in its own right, but will require new technologies and analysis techniques to be distinguished from a dark matter signal, such as the expected annual modulation of the DM rate [95] and directional detectors (see *e.g.* the review found in [96]). Directional DM detectors would further open up the tantalizing potential to map out the local DM structure of the Galaxy.

Currently, the most stringent SI bounds for $\gtrsim 10$ GeV dark matter masses are from liquid xenon (LXe) and liquid argon (LAr) detectors employing time projection chamber (TPC) technology. Charge and phonon detectors are able to reach lower DM masses and are expected to reach sensitivity for dark matter masses between 0.5–5 GeV to within a decade of the neutrino fog, limited by cosmogenically activated isotopes

including ^{3}H and ^{32}Si, ^{210}Pb, and by dark counts. Isotopically purified LAr detectors [98] or phase change detectors such as bubble chambers [99] can provide powerful background-discriminating technology and the combination of scalability, low threshold, and background discrimination *at low threshold* could allow noble-liquid bubble chambers to explore the neutrino fog in the 1–10 GeV WIMP mass range.

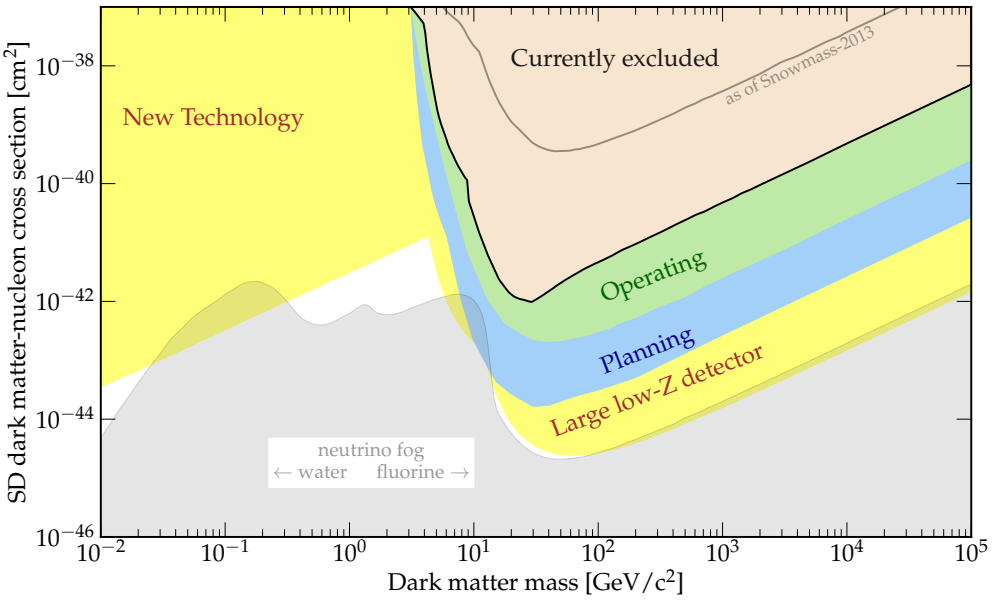

Figure 5-19. *Combined Spin-dependent dark-matter nucleon scattering cross section space for scattering with neutrons or protons. Current 90% c.l. constraints are shaded beige, whereas the reach of currently operating experiments are shown in green (LZ, XENONnT). Future experiments are shown in blue (PICO-500, XLZD) and yellow (Snowball, PICO-100 ton). The neutrino fog for a water or fluorine target is shaded light grey. From Ref. [97].*

Figure 5-18 shows the current, operating, and future projected 90% CL constraints for WIMP DM interacting spin-independently [97]. The beige regions show the current best exclusion for each mass, combining previously reported limits [100–115], as collected by Ref [116]. A measure of the incredible progress of the past decade is provided by the comparison with the grey line from Snowmass 2013 [117]. The projected reach of currently operating experiments is shaded in green, whereas proposed upgrades are shown in blue (including SuperCDMS, DarkSide-LowMass, SBC, XLZD, and ARGO) and the reach of proposals based on new technologies are shaded in yellow (Snowball and Planned× 5). The region corresponding to the neutrino fog for a xenon target is shaded light grey.

Similarly, Figure 5-19 shows the current, operating, and future projected 90% CL constraints for WIMP DM interacting spin-dependently [97]. Shaded in beige is the union of the currently excluded parameter space, led by LXe TPCs and freon-based bubble chambers [103, 118–120, 120–128], as collected by Ref [116]. The expected reach of currently operating experiments is shaded green, and future proposed experiments are shaded blue (including PICO-500 and XLZD) and yellow (Snowball and PICO-100 ton). The region corresponding to the neutrino fog for a water or fluorine target is shaded light grey.

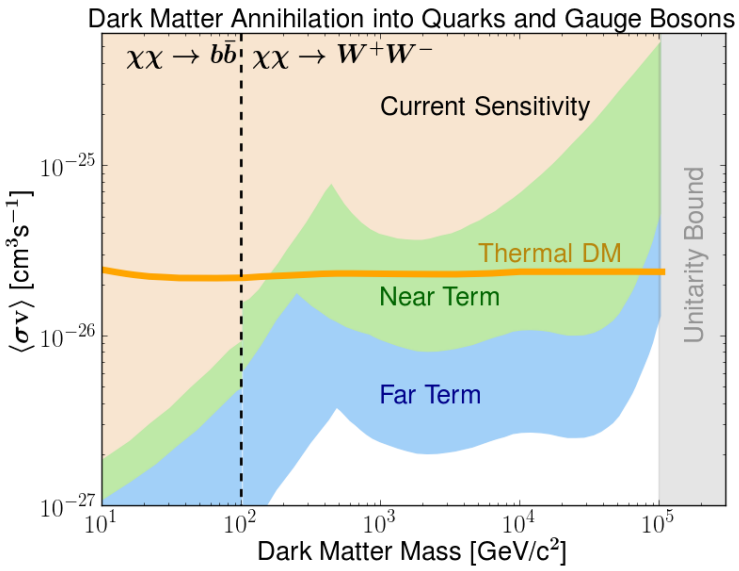

Figure 5-20. *Limits on WIMP annihilations into pairs of bottom quarks (for masses below ∼ 100 GeV and W bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region indicates near future gains based on planned missions, and the blue shading indicates the reach that would be enabled by long term investments in ground- and space-based observatories. From the CF1 report [1].*

Taken together, Figures 5-18 and 5-19 illustrate the exciting prospects for direct searches in the WIMP regime, with a suite of experiments based on different technologies capable of probing WIMP dark matter all the way down and into the neutrino fog.

Indirect searches for dark matter play a very important role in covering the parameter space. At lower masses, as discussed above, measurements of the CMB have a key role in constraining the viable portals to communicate with the SM. At the highest masses, indirect detection achieves sensitivity to WIMP parameter space that is inaccessible to direct or collider searches, and in general provides a broadly model-agnostic probe of thermal freeze-out scenarios. The most effective messengers of WIMP annihilation are gamma rays (which point back to their origin, giving an additional analysis handle) and energetic anti-matter signals in cosmic rays. Especially for higher DM masses, where abundant energy is available to produce the full range of SM particles, indirect signals are generically expected to be multi-messenger and multi-scale [129].

The rate of annihilation depends on the underlying microphysics, which determines both the rate into each specific annihilation channel as well as its dependence on the relative velocity between the annihilating dark matter particles. Dark matter making up the halos of galactic structures is typically highly non-relativistic ($v \sim 10^{-4} - 10^{-3}$), and thus s-wave annihilations (for which $\langle\sigma v\rangle$ is v-independent) typically dominate over annihilations at higher partial wave. Additional challenges involve determining the dark matter distribution along the line of sight of an indirect search, which strongly impacts the rate of annihilation, since $\langle\sigma v\rangle \propto \rho_\chi^2$. This systematic uncertainty benefits strongly from advances in simulation of galaxy formation. Modeling of astrophysical backgrounds with sufficient precision as to be able to distinguish a subtle signal of dark matter annihilation or decay from more prosaic astrophysical processes is also a key ingredient (see Refs. [1,130,131] for further discussion); this is already manifest in a number of puzzling excesses in indirect searches [130].

Gamma rays may be detected both by space- and ground-based telescopes. The space-based Fermi-LAT is optimized to reconstruct gamma rays from 1 – 100 GeV and is effectively able to observe the entire sky as it orbits, whereas ground-based air and water Cherenkov telescopes are effective at energies above $\sim$ 100 GeV. Most current Cherenkov telescopes are located in the Northern Hemisphere, but Southern Hemisphere locations are advantageous for observing both the Galactic Center and the central dense region of the Milky Way's dark matter halo. For s-wave annihilation, Fermi-LAT has already strongly constrained the thermal freeze-out cross section for masses up to $\sim$ 100 GeV based on observations of the Milky Way's dwarf spheroidal galaxies (e.g. [132,133]), which are (as measured by stellar dynamics) dark matter rich and baryon poor, limiting the expected sources of background. These limits are expected to improve in the near future, as surveys such as Vera Rubin discover (about a factor of two) more dwarf spheroidal galaxies [134].

In the near future, the SWGO [135] (water Cherenkov) and CTA [136] (air Cherenkov) telescopes, successors using similar technology to the successful HAWC and VERITAS Cherenkov telescopes but with larger installations and Southern Hemisphere sites, have the potential to probe the thermal freeze-out scenario up to 10s of TeV masses (depending on the annihilation channel) [137,138], approaching the 100 TeV scale where we can begin to set unitarity-based limits on the capacity for freeze-out to generate the correct relic abundance. Further in the future, APT [139] is a concept for a space-based successor instrument to the Fermi-LAT (with a demonstrator suborbital mission scheduled for 2025), which aims to improve sensitivity at lower masses by an order of magnitude. Figure 5-20 shows the limits on WIMP annihilations into pairs of bottom quarks (for masses below $\sim$ 100 GeV) and W bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region shows improvements expected in the near future based on planned Cherenkov observatories and including new populations of dwarf spheroidal galaxies expected to be discovered by Rubin LSST. The blue shading indicates parameter space that could be probed by longer term investment into future large Cherenkov arrays and new space-based missions. The orange band indicates the benchmark cross section corresponding to the correct relic abundance from freeze-out. The gray "unitarity bound" region corresponds to the general mass range (the exact bound is model-dependent and depends on assumptions about long-range forces, compositeness of the dark matter, etc.) in which obtaining the correct dark matter abundance via freeze-out becomes inconsistent with unitarity in the early universe, under standard assumptions for the cosmological history.

Cosmic-ray experiments (primarily AMS-02) currently set competitive constraints on heavy annihilating or decaying DM, with systematic uncertainties independent from gamma-ray probes. In the near future, GAPS [140] will provide the first dedicated search for low-energy anti-deuterons, which are expected to have only tiny astrophysical backgrounds and could serve as a very clean discovery channel, and HELIX [141] will provide new constraints on cosmic-ray propagation. Far-future proposals ALADInO [142,143] & AMS-100 [144] involving superconducting magnetic spectrometers seek greatly improved sensitivity to anti-deuterons and anti-helium; GRAMS [79] would employ a liquid-argon TPC to search for both gamma rays and charged cosmic rays, and ADHD [64] is a proposal to pursue a novel delayed-annihilation signal from anti-nuclei in a helium detector. Accelerator experiments including NA61/SHINE [145], ALICE [146], LHCb [147], and AMBER [148] can also provide complementary measurements to constrain cosmic-ray production and propagation, helping to reduce systematic uncertainties in both signals and backgrounds.

5.4.4 Ultra-Heavy Dark Matter

Measurements of baryon acoustic oscillations and the CMB set some of the strongest limits on the total baryonic fraction of matter in the universe. The sound waves of the primordial plasma have compressions due to gravitational attraction and the restoring force due to plasma pressure causes the following rarefactions.

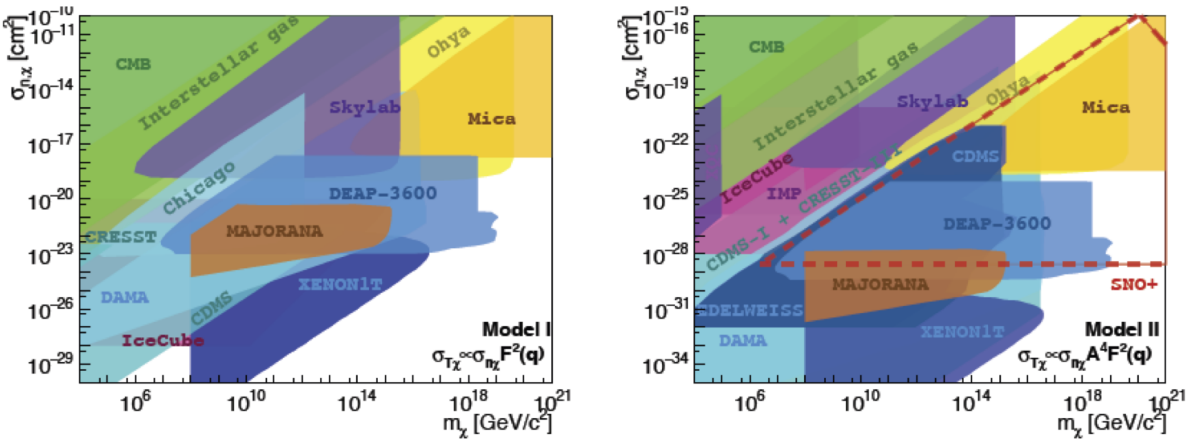

Figure 5-21. *Ultra-heavy dark matter can be studied through a range of terrestrial experiments, indirect detection experiments, and cosmic probes. The sensitivity of direct detection experiments is primarily limited by the cross-sectional area of the detectors due to the fact that the kinematics of nuclear recoil asymptotes to fixed recoil energy for large dark matter masses. From Ref. [149].*

The higher amplitude in the odd-numbered power spectrum peaks indicate that most of the gravitating matter does not exhibit pressure when compressed and is hence not electromagnetically charged like protons or electrons. So even if dark matter took the form of non-luminous, cold baseballs (a model that is difficult to constrain observationally), these baseballs would still have to be made of some non-standard exotic particles.

For masses beyond the unitarity limit, it becomes a challenge to produce dark matter via freeze-out. One interesting set of models produces dark matter in this mass range as composite blobs of more fundamental particles, held together by new dark forces. Cosmic observation of the CMB and interstellar gas set robust constraints at large cross sections, while observations of extreme astrophysical environments can also constrain the presence of UHDM. Both the searches for WIMPs described in the previous subsection as well as more specialized searches have sensitivity to this UHDM regime, depending on the strength and nature of its interactions with the SM (see Ref. [129] for a more in-depth discussion). For strongly interacting blobs, a typical event in a terrestrial experiment could involve multiple scattering, necessitating new analysis techniques and implying that the area of the detector is the most relevant factor rather than its volume. For indirect searches, high energy neutrinos and cosmic rays become especially important at high masses. Cascades of secondary particles from high-energy primaries often lead to observable indirect signatures at much lower energies than the DM mass, such that the gamma-ray telescopes described above have sensitivity to DM masses much higher than their target energy ranges. This situation represents an ongoing theoretical challenge, requiring new techniques for accurate predictions to take advantage of the opportunity to observe rich and complementary multi-wavelength and multi-messenger signals [129]. For DM masses of order GUT-scale, however, the secondary photons *en route* to Earth travel unscathed. Accordingly, AugerPrime and next-generation cosmic ray observatories anchor unique DM indirect detection experiments which are free of astrophysical background: a clear detection of an extreme energy photon would be a momentous discovery [150]. Fig. 5-21 shows the current and projected experimental regions of ultra-heavy parameter space accessible to direct searches.

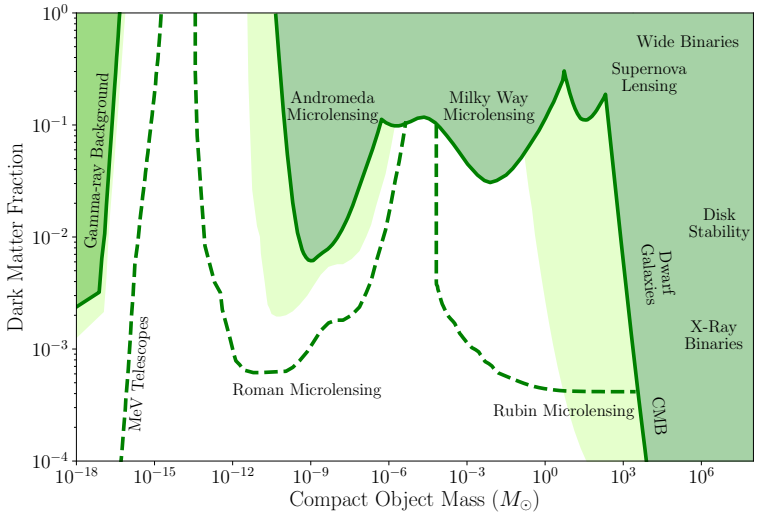

Figure 5-22. *Some fraction of the dark matter could take the form of macroscopic, compact objects such as primordial black holes. Cosmic observations provide sensitivity to primordial black holes over a wide range of masses (green regions). Projected improvements in sensitivity coming from future microlensing and gamma-ray searches are indicated with dashed green lines. From the CF3 report [3].*

5.4.4.1 Dark Matter Beyond the Planck Scale

Dark matter at the Planck mass ($\sim 10^{-5}$ g) and above is very difficult to detect directly due to its extremely low flux. Detection techniques rely on scattering to be mediated via long range forces so that effects can be seen in sparsely instrumented detectors with large collecting area. For example, if dark matter had a long range Yukawa force 10^3 times greater than gravity, then interactions of 10 kg mass dark matter with the 10 kg scale mirrors of the LIGO gravitational wave observatory could potentially be detected as the clumps traversed within the near field of the 4 km long interferometers [151]. Proposed larger observatories such as the 40 km long Cosmic Explorer or laser ranging between astroids would provide a larger collection area [152].

Heavier compact constituents of dark matter including primordial black holes (PBHs), can be detected through cosmic probes (Figure 5-22). PBHs with masses of $\sim 10^{-18}\, M_\odot$ ($\sim 10^{15}$ g) should be evaporating today, creating short bursts of Hawking radiation in the GeV-TeV range that could be observed with space-based and ground-based gamma-ray telescopes, as well as neutrino observatories. For higher masses, gravitational micro-lensing provides the most sensitive probe of the abundances of PBHs. Near-future observatories such as Rubin LSST have the potential to radically increase the sensitivity of micro-lensing searches if scheduled optimally [153]. Sub-solar mass PBHs may be detected through microlensing with Rubin LSST and other observatories or through mergers with next-generation gravitational wave detectors. High redshift searches with optical or gravitational wave probes may also reveal the existence of primordial black holes.

5.4.5 Delve Deep, Search Wide

The parameter space of dark matter models is vast, yet experiments which will provide significant inroads into this space are relatively inexpensive. The Cosmic Frontier plans to explore dark matter parameter space over the next decade through targeted searches to make deep progress on high-priority science targets, and an expanded portfolio of cosmological and astrophysical observations, and small pathfinder experiments implementing new detector technologies to search wide and provide broad coverage of the range of possibilities. This strategy will cover large regions of model-space, and could easily lead to a transformational discovery within the next decade (see the lower panel of Figure 5-2).

The WIMP and the QCD axion remain highly motivated and clear experimental targets. Tremendous progress has been made in the past two decades in liquid noble detectors and a multi-national collaborative project would continue this momentum to push sensitivity down to the solar neutrino background. Concurrently, indirect searches with proposed TeV gamma-ray observatories would conclusively test the self-annihilation cross section which defines the WIMP model, up to the scale where unitarity bounds become relevant. In the axion field, a portfolio of complementary techniques including NMR, lumped element resonators, cavity resonators, quantum sensors, and novel scattering targets would cover most of the remaining parameter space of the QCD models that solve the strong-CP problem. Axion-like particles are also well-motivated with a parameter space that can be targeted over the next ten years and beyond. Concurrently, a portfolio of new technologies including CCDs, novel materials as scattering targets, and ultra-low threshold readouts including low heat capacity transition edge sensors, kinetic inductance detectors, and Josephson junction-based sensors, is being assembled to test a broad range of portal dark matter models. Pathfinder experiments using AMO techniques including atomic clocks, atom interferometers, and opto-mechanical oscillators are also being developed. Cosmic and indirect probes will complement and inform all of these searches, while broadly exploring parameter space and phenomena that are currently inaccessible to terrestrial experiments. With the exception of the medium-scale multi-national WIMP experiments, all of the other terrestrial dark matter experiments would be best characterized as "small." Similarly, modest investments in theory, computation, and cross-disciplinary analysis infrastructure would enable access to dark matter science in the larger cosmic surveys program.

All combined, a coordinated U.S. experimental program to delve deep and search wide for dark matter might reasonably be expected to cost as much as a single large experiment. Such a comprehensive and coordinated program would be very reasonably justified by its broad science reach in addition to its broader impacts in technology development, contributing to the quantum ecosystem, and training the next generation of experimental hardware specialists.

Investment in new experimental techniques for both low-mass portal dark matter, axions, and more general bosonic waves has been slow to ramp up as most DOE/NSF dark matter funding has been invested in the larger dark matter experiments as per the recommendations of the previous P5 report. Identifying this gap in the U.S. dark matter strategy, private foundations including the Simons Foundation, the Heising-Simons Foundation, and the Moore Foundation have begun to invest in university programs to fund dark matter instrumentation R&D including pathfinder experiments at the $10M level. Some of the technology development and instrumentation work has also been enabled by leveraging various quantum programs, given that ultraweak dark matter interactions are a natural target for new quantum sensor technology. Cross-disciplinary engagement with neighboring scientific communities including atomic, molecular, and optical physics, condensed matter physics, and quantum information science have been facilitated by DOE-OHEP's QuantISED program and by the National Quantum Initiative Science Research Centers. This collaborative research enables the direct transfer of novel detection concepts as well as mature detector technologies from neighboring fields to HEP applications as well as the direct engagement of hardware experts who are able offer fresh perspectives on the detection challenges.

A positive development has been two DOE Basic Research Needs workshops, the first creating the DMNI program to fund small dark matter experiments of a scale smaller than the medium-size LZ and SuperCDMS experiments, and the second aimed at identifying instrumentation R&D needs including quantum sensing for fundamental physics. The DMNI program has funded the technical design studies of a limited portfolio of small experiments as recommended in the previous P5 report. These include the axion experiments ADMX-Extended-Frequency-Range and DM-Radio, the 1 eV threshold Oscura silicon CCD experiment, the sub-eV threshold TESSERACT program that utilizes novel condensed matter targets, as well as the fixed target experiments LDMX and CCM that probe portal dark matter models via light dark particle production. While these experimental concepts have not yet proceeded to project status, the DMNI program provides a prototype for implementing a broad and coordinated dark matter program with a portfolio of complementary experiments to target different regions of unprobed parameter space. Continuation of DMNI or similar programs targeting smaller pathfinder experiments is therefore a key element of the 'delve deep, search wide' strategy for discovering the nature of dark matter.

Similar support could significantly strengthen cosmic and indirect probes of dark matter. These approaches have the potential to yield large scientific dividends by searching wide ranges of dark matter parameter space. For example, Rubin LSST has enormous potential to discover new physics beyond the prevailing cold dark matter paradigm [28,45]. Rubin LSST can measure the distribution of dark matter on unprecedentedly small scales, thereby probing microscopic properties of dark matter, including thermal particle mass, self-interactions, interactions with radiation, and quantum wave features. Microlensing measurements will directly probe primordial black holes as a component of dark matter. The planned CMB-S4 [17] and future Spec-S5 [11] and CMB-S5 projects will extend access to rich dark matter particle physics. For instance, detection of additional relativistic degrees of freedom by CMB-S4 would imply the existence of a dark sector. However, building the infrastructure to perform dark matter analyses with these experimental facilities requires dedicated support for experimental collaborations, theoretical research, and large numerical simulations (which are crucial to distinguish novel dark matter physics from baryonic astrophysics). Rubin LSST and other cosmology facilities should be explicitly identified as dark matter facilities to enable what promises to be an exciting decade of dark matter research.

5.5 Neutrinos

Cosmic probes can provide crucial information about the neutrino sector and exhibit a high degree of complementarity to terrestrial probes [154]. Cosmology is sensitive to the number and masses of the neutrinos through their impact on the evolution of the Universe, providing information that is currently inaccessible through other means.

5.5.1 Cosmic Measurements of Neutrino Masses

The current cosmological limits on the sum of the neutrino masses is $\sum m_\nu < 0.12$ eV as obtained using cosmic microwave background, baryon acoustic oscillations, supernova Ia, and large scale structure measurements. Additional information on impact of cosmological neutrinos on the growth of structure both will be obtained from high redshift galaxy surveys. CMB-S4 will reach sensitivity $\sigma(\sum m_\nu) < 0.02$ eV and if the data indicate a mass sum < 0.1 eV, this would rule out the inverted neutrino mass hierarchy which predicts higher mass sum, providing key synergy with long baseline neutrino experiments and important input to searches for neutrino-less double beta decay attempting to unravel whether neutrino masses are fundamentally Majorana or Dirac in nature. A Stage V Spectroscopic Facility would reach similar constraints from an independent

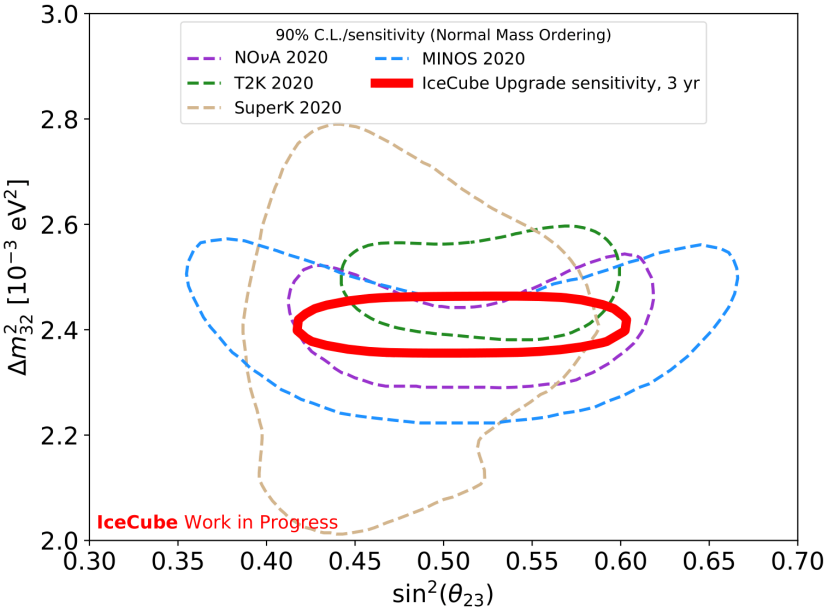

Figure 5-23. *Measurements of* $\sin^2(\theta_{23})$ *and* Δm^2_{32} *with the IceCube Upgrade (inner fiducial volume) comparing with long-baseline neutrino oscillation facilities and other Cherenkov detectors. From the CF7 report [7].*

experiment at $2 < z < 5$. Further gains in accuracy on $\sigma(m_\nu)$ beyond what CMB-S4 and Spec-S5 each will achieve will be limited by the currrent τ prior, unless that parameter is constrained better. Proposals to achieve such improvements are described in the CF4 report [4]. Higher statistics observations of the matter distribution at high redshifts could be measured by line intensity mapping surveys (in 21-cm and mm-wave) and other probes, such as future high resolution CMB imaging, and would reach resolution $\sigma(\sum m_\nu) < 0.01$ eV.

5.5.2 New Opportunity: High-energy neutrinos

The discovery of TeV-PeV astrophysical neutrinos opens up unique opportunities to probe the neutrino sector at energy scales not accessible with laboratory neutrino beams. High-energy neutrinos from IceCube were used to discover the Glashow resonance and measure the high-energy neutrino-nucleon cross section and inelasticity distribution. Future statistics will allow further tests of the Standard Model neutrino physics between 1 TeV and 10 PeV. In addition, ultrahigh energy neutrinos (UHE; $\gtrsim$ 100 PeV neutrinos) have been long-predicted but remain undetected. They provide a path to probe weak-scale physics at center-of-mass energies above 50 TeV. Next-generation UHE neutrino experiments have the potential to detect these neutrinos and push the forefront of neutrino physics [155].

Observations of neutrino flavors and neutrino-antineutrino ratios may probe BSM physics [156]. The search for BSM neutrino interactions with other neutrinos or with dark matter may shed light on the UV theory of neutrinos and the origins of their low mass. Such new interactions could be observed for example via spectral distortions in the cosmic neutrino flux in the PeV-EeV range as they scatter on the cosmic neutrino background. Deviations from equal admixtures of the 3 neutrino species might occur at various energy

thresholds when new interactions turn on. Neutrino production measurements from CERN's Forward Physics Facility will provide important information to calibrate the atmospheric neutrino background produced by cosmic rays scattering on nuclei in the atmosphere and thus allow cleaner detection of cosmic neutrinos [157, 158]. Finally, at GeV energies, the upcoming IceCube Upgrade and other future cosmic neutrino experiments will provide neutrino oscillation sensitivity complementary to long baseline experiments (see figure 5-23).

5.6 Exploring the Unknown: New Particles, New Fields, New Principles of Nature

5.6.1 Dark Radiation

Dark radiation can be observed in various cosmological epochs while it is still relativistic, before its kinetic energy redshifts away. Within the Standard Model (SM), neutrinos form an important component of dark radiation, and constraints from their impact on the cosmic evolution at the epochs of Big Bang Nucleosynthesis and the CMB provide powerful constraints on the number of neutrino species, typically reported as $N_{\rm eff}$, the "effective number of neutrinos". In addition, determinations of the dark radiation content of the Universe provide unique opportunities to search for particles produced in the early universe, even when such particles are extremely weakly interacting with the SM. A few well-motivated examples include light particles invoked by models that aim to explain the physics of a dark sector, address the strong CP problem, solve the weak hierarchy problem, account for short baseline neutrino anomalies, and/or models of warm inflation.

Figure 5-24 shows the current measurement of $\Delta N_{\rm eff}$, and future prospects from operation of the Simons Observatory and CMB-S4, via temperature and polarization measurements on small angular scales over a large fraction of the sky. The projections indicate the contribution to $\Delta N_{\rm eff}$ from a single species of one of three different types of relic particles (Goldstone or vector bosons and Weyl fermions) for a particle which was initially in chemical equilibrium with the SM plasma, but whose interactions decoupled at freeze-out temperature T_F. Current observations constrain $\Delta N_{\rm eff} < 0.3$ (at 95% c.l.), which probes individual particles decoupling during or after the QCD phase transition (at ∼100MeV scale). The next generation of CF experiments is poised to reach very exciting levels of sensitivity to $\Delta Neff$. CMB-S4 will achieve $\Delta N_{\rm eff} < 0.06(95\%)$ which would be sensitive to new particles with spin decoupling at 100 GeV and real scalars at 1 GeV, just prior to the QCD phase transition. The later is particularly important for axion-like particles coupling to heavy fermions, where CMB-S4 would be the most sensitive experimental or observational probe by orders of magnitude. CMB-S4, by reaching a precision of $\Delta N_{\rm eff} \lesssim 0.06$, will thus be able to discover or rule out the existence of such weakly-interacting particles which have frozen out back to the temperature of the beginning of the QCD phase transition (~ 0.5 GeV). Moreover, a Stage V Spectroscopic Facility would reach similar constraints from an independent experiment at $2 < z < 5$ which could be combined to achieve even higher precision. Building off CMB-S4, future experiments reaching a precision of 0.027, as could be achieved e.g. by a CMB-S5 facility and future LIM surveys, would be sensitive to such particles freezing out all the way back to the electroweak scale.

Relativistic dark particles can also be produced late in cosmological time from a variety of sources including dark matter decay, dark sector phase transitions, and cosmic string decays [160] and could be detected with various wave dark matter detector technologies. For example, quintessence models promote the dark energy from a cosmological constant to a dynamically evolving field which is slowly rolling in a scalar potential, triggering a new epoch of cosmic inflation. A natural question is then whether this quintessence field is slowly rolling in a flat potential, or if it is rolling in a steeper potential but slowed down by dynamical

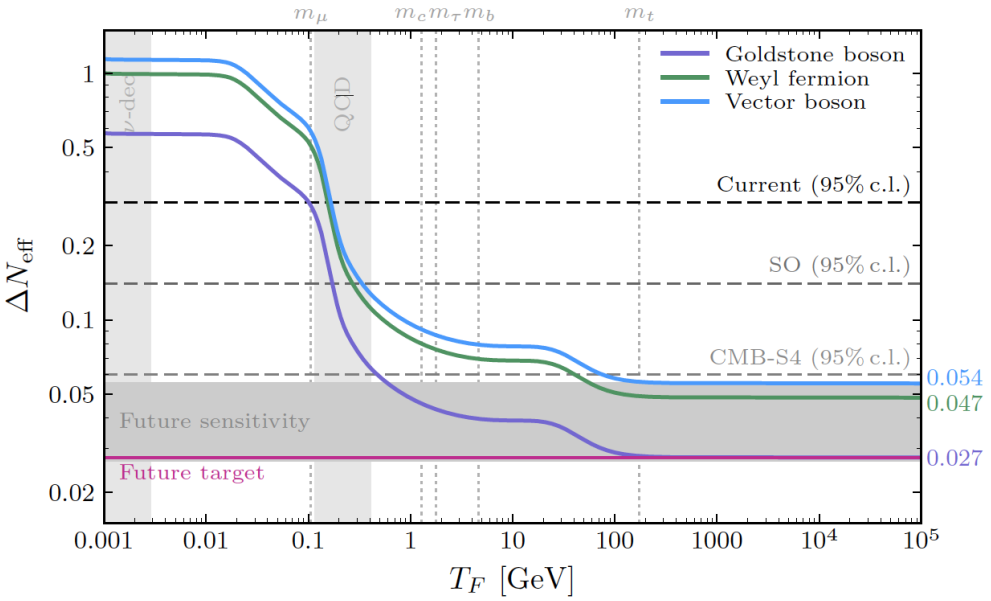

Figure 5-24. *The presence of additional relativistic BSM particles beyond the three known neutrino species impacts the power spectrum of acoustic oscillations in the primordial plasma. Measurements of the CMB can be used to discern the presence or absence of these exotic degrees of freedom, parameterized as $N_{\rm eff}$, the effective number of relativistic species active during this epoch. Some representative models are shown in this plot along with the current constraints on additional particles and projections for the Simons Observatory and CMB-S4. From Ref. [159].*

friction. In this warm dark energy scenario, the ongoing interactions during the slow roll in the present day universe would populate the universe with dark radiation in the form of relativistic, low mass particles with temperature and energy density typically characterized by the milli-eV scale (10 K) of the dark energy density [161]. This late injection of entropy is not constrained by bounds on CMB distortion at earlier times. Searches for this 10 K bath of exotic particles with repurposed, low-threshold dark matter detectors would nicely complement the cosmic surveys studies of the evolution of cosmic acceleration.

5.6.2 The Highest Energy Particles

Cosmic particles above 100 TeV provide a unique window into fundamental particle physics at energy scales beyond those reachable by terrestrial accelerators. In addition to providing indirect probes of dark matter in various annihilation or decay channels and the measurements of the neutrino sector described elsewhere in this report, observatories of cosmic rays, neutrinos, gamma rays, and gravitational waves together constitute a rich, multi-messenger program to explore the unknown through the study of the highest energy particle astrophysical phenomena in the universe.

The increased precision of the measurement of ultra high energy (UHE; $> 10^{18}$ eV) cosmic rays represents a unique opportunity to study particle physics at the very edge of the Energy Frontier via natural accelerators [162]. In the area of hadronic shower physics, a long standing puzzle is the mysterious excess of muons in UHE cosmic ray air showers beyond what is expected from extrapolations of hadronization models calibrated with LHC and other collider data [163]. Ongoing upgrades of the Pierre Auger Observatory and

IceCube(-Gen2) with the planned enhancement of its surface array will provide greater resolution of the electromagnetic and muonic flux in air showers as well as measurements of the depth of shower maximum which provides complementary information on the initial particle species. The proposed Forward Physics Facility at the LHC [157, 158] would also provide muon and electron neutrino shower data which could be used to calibrate kaon production in high energy hadronic showers. Higher than expected kaon production rates would enhance the muon production by reducing the production of neutral pions which siphon energy into the electromagnetic portion of the shower. Whether the puzzle is resolved by a better understanding of the fragmentation process or potentially by BSM physics at high center-of-mass energies, these data will better inform the modeling and design of future high energy colliders. Next-generation UHECR experiments, such as the Global Cosmic-Ray Observatory (GCOS), the Probe of Extreme Multi-Messenger Astrophysics (POEMMA), and IceCube-Gen2 with its surface array, will allow for even more precise measurements of particle physics at energies well-beyond the reach of human-made accelerators. The high boosts and large, cosmological propagation scales of UHE cosmic particles also allow for powerful tests of Lorentz and CPT symmetries by searches for spectral distortions in the flux of UHE cosmic rays, very-high-energy gamma-rays ($0.1 - 100$ TeV photons), UHE gamma-rays (> 100 TeV photons), and cosmic neutrinos.

High energy gamma rays and neutrinos additionally offer probes of new physics including the decays of super-heavy relics left behind from the Big Bang, cosmic strings, and axion-photon conversion in large-scale magnetic fields. Next-generation gamma-ray telescopes such as the Southern Wide-field Gamma-ray Observatory (SWGO), the Cherenkov Telescope Array (CTA), and the All-sky Medium-Energy Gamma-ray Observatory (AMEGO) will open up the access to new sky regions and energy ranges, and advance fundamental physics studies with significantly improved sensitivities. Next-generation UHE neutrino ($>$ 100 PeV neutrino) observatories led by the U.S. community such as the IceCube-Gen2, The Radio Neutrino Observatory in Greenland (RNO-G), POEMMA, Beam forming Elevated Array for COsmic Neutrinos (BEACON), the Payload for Ultrahigh Energy Observations (PUEO), and the Extreme Neutrino Observatory (Trinity), have the potential to discover UHE neutrinos and use them to probe fundamental physics.

The concept of multi-messenger astronomy is finally being realized with co-detection of gamma rays and gravitational waves in a binary neutron star merger and the co-detection of neutrinos and gamma rays in a blazar flare [164]. Studies of these violently energetic astrophysical events may reveal new physics including the nature of quark matter in neutron stars, the possible accumulation or scattering of dark matter on these objects, and the production of exotic particles in large astrophysical large magnetic fields. Various tests of Einstein gravity may lead to discoveries of relevance to cosmology including modifications to the understanding of cosmic acceleration and the distribution of matter. As remarked in the dark matter section of this report, while a 20-year strategic plan is being developed for most cosmic particle channels across broad ranges in energy, an ongoing concern is the lack of coverage for MeV-GeV gamma rays beyond that provided by the aging Fermi telescope.

5.6.3 Probes of Fundamental Physics with Gravitational Waves

One of the most significant scientific developments of the past decade is the emergence of gravitational wave detection as a powerful new tool to study fundamental physics. In addition to the extensive menu of gravitational physics that will be studied by current and future gravitational wave observatories, the new GW probes will also provide unique and independent information in a number of areas of interest to the high energy physics community. For example, neutron star binary mergers will probe the neutron star equation of state and may also be sensitive to accumulations of various types of dark matter within the neutron stars. Binary mergers provide a new standard candle for measurements of cosmic acceleration with systematics independent of those of the currently used optical probes. Alternatively, the neutron star

merger's gravitational wave luminosity distance may be combined with redshift information from the host galaxy to provide new measurements of the Hubble parameter at large redshifts.

Gravitational wave observatories will also provide unique probes of early universe phase transitions which may have happened at times prior to big bang nucleosynthesis – a period about which not much information is currently available. These phase transitions may produce a stochastic background of gravitational waves from boiling of the vacuum during strongly first order phase transitions or from the oscillations and decay of cosmic strings and other topological defects which may form during these phase transitions. The resulting gravitational wave power spectrum will provide information about these new fundamental energy scales which, once discovered will provide concrete new information for BSM model building. As a concrete example, with its lower frequency signal response, LISA will be able to search for a stochastic gravitational wave background and provide evidence for an extended Higgs sector causing the a first-order electroweak phase transition. Cross-correlating the gravitational wave background with the matter power spectrum may also reveal the dynamics of BSM early universe physics.

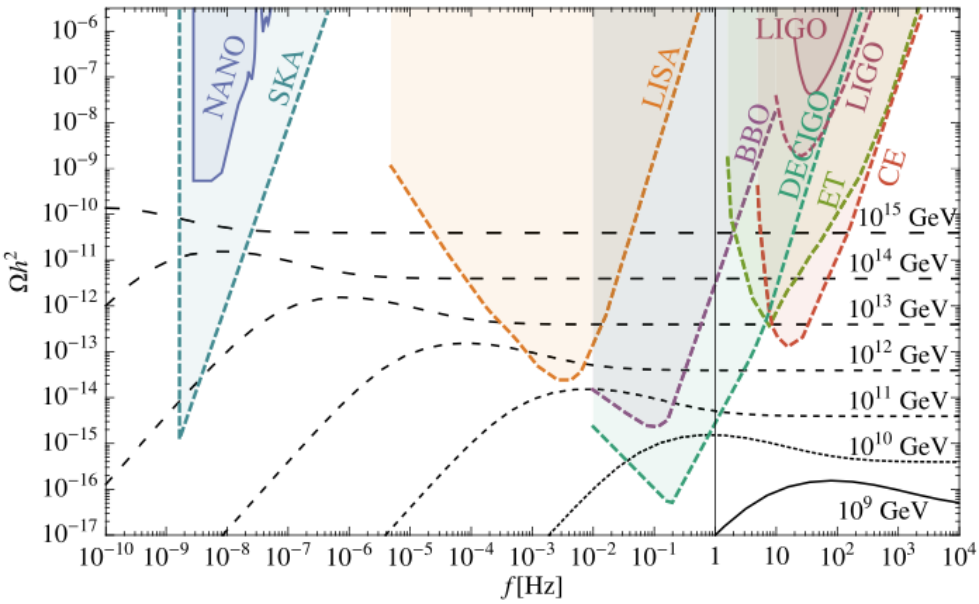

Figure 5-25. *Future gravitational wave observatories will be sensitive to the stochastic spectrum of GWs created by cosmic string decay or by boiling of the vacuum in first order phase transitions. This plot shows an example of the high energy symmetry breaking scales that can be probed in a particular model of thermal leptogenesis. In other models, the predicted spectrum may be peaked at certain frequencies, in which case observatories optimized for specific frequency ranges may have greater sensitivity. From reference [165].*

The signal will be visible even through the cosmic microwave background which obscures photon probes of earlier cosmological epochs. Even phase transitions which might happen in secluded dark sectors which have no BSM couplings to standard model particles can still be probed due to the universal coupling of gravity to all matter and energy. As example, figure 5-25 shows how a broad program of new gravitational observatories targeting different frequency ranges can probe deeply into the predicted power spectrum of phase transitions at energy scales from $10^{10} - 10^{15}$ GeV for various models of thermal leptogenesis. The observatories range from pulsar timing arrays at the lowest frequencies to space-based experiments at sub-Hz frequencies to next generation ground-based interferometers at the highest frequencies.

New physics of early universe phase transitions may even be observed with the current generation of gravitational wave observatories. As a case study, LIGO may already be sensitive to the stochastic power spectrum from Peccei-Quinn phase transition in QCD axion models if a particularly violent phase transition occurs at relatively low energies around 10^8 GeV where the red-shifted frequency spectrum of the GW emission becomes matched to the LIGO band. If the energy scale of the phase transition can be determined in this way, then the axion model gives a firm prediction for the mass of the dark matter axion and will narrow the search window for the direct detection experiments from 10 decades in mass down to a single decade. A confirmation of a dark matter signal would then provide corroborating evidence for the axion solution to the strong-CP problem. Alternatively, if the dark matter signal is discovered first in the post-inflationary scenario with mass between $10^{-5} - 10^{-2}$ eV, then this provides a firm target for the sensitivity and frequency range needed for future gravitational wave observatories to observe the phase transition. Similar strategies may be employed to search for new fundamental energy scales and test see-saw models in other contexts.

The collection of currently operating gravitational wave observatories include the LIGO facilities in Livingston, Louisiana and Hanford, Washington, along with the Virgo facility in Italy and the recently constructed, underground KAGRA observatory in Japan. LIGO-India will also be online at the end of the decade, and the space-based LISA observatory is planned for the next decade. Pulsar timing arrays operating at lower frequencies include NANOGrav in North America, the Parkes Pulsar Timing Array in Australia, the European Pulsar Timing Array, and the Indian Pulsar Timing Array, while plans are being made for a future Square Kilometer Array. Near term plans for the U.S. gravitational wave community include the LIGO Voyager upgrade in which the existing fused silica mirrors may be replaced with crystalline silicon mirrors which can be more easily thermalized to avoid geometric distortions from heating, and the Cosmic Explorer proposal which would increase the interferometer arm length and hence antenna size from 4 km to 40 km. The AMO community is also developing long baseline atom interferometry as a potential new technique targeting lower frequency gravitational waves as well as oscillatory forces from dark matter in the 1 Hz band. The MAGIS-100 pathfinder experiment will utilize a 100 m vertical beamline access shaft at Fermilab with possible future expansion to a 2 km drop at SURF and eventually a space mission to avoid terrestrial Newtonian noise.

Participation of the HEP community may be key to the success of these ambitious projects and to ensure that optimizations for HEP science can be integrated into the designs, data pipelines, and operations plans. As an example, searches for stochastic gravitational wave power can be performed within a narrow band to reject noise as opposed to measurements of time domain waveforms which intrinsically require broader bandwidth template searches. Similarly, searches for kg-mass dark matter passing within an antenna length of the interferometers will need dedicated data pipelines and analyses. More direct engagement by national laboratories may also be critical for the construction of future large scale GWO projects.

5.7 Conclusion

As we have described in this report, the coming decade will provide us with tremendous opportunities to make new breakthroughs in our knowledge of fundamental physics through Cosmic Frontier experiments. With a scientific scope directly encompassing four of the five 2014 P5 science drivers of the field (dark matter, dark energy and cosmic acceleration, neutrinos, and exploring the unknown), much of the discovery potential of the HEP community in the twenty-first century is driven by accomplishments in the Cosmic Frontier. The comprehensive plan envisioned by our community will ensure that this potential is fully realized. Taking full advantage of the scientific opportunities will require us to simultaneously pursue the strategies of Aiming High, Delving Deep, and Searching Wide. These strategies complement and reinforce each other: by developing powerful experiments that are able to simultaneously address many key science

questions, pursuing definitive constraints on the most promising scenarios for Beyond the Standard Model physics, and exploring new regions of parameter space where the truth may lie, we can ensure that we will make new discoveries and approach ever closer to a full understanding of the fundamental physics of our Universe.

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6

Energy Frontier

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Executive Summary

The Energy Frontier (EF) aims at investigating the fundamental physics of the Universe at the highest energies or – equivalently – the shortest timescales after the Big Bang. We investigate open questions and explore the unknown using various probes to discover and characterize the nature of new physics, through the breadth and multitude of collider physics signatures. While the naturalness principle suggests new physics to lie at mass scales close to the electroweak scale, in many cases direct searches for specific models have placed strong bounds around 1-2 TeV. Thus, the energy frontier has moved beyond the TeV scale and the exploration of the 10 TeV scale becomes crucial to shed light on physics beyond the Standard Model (SM).

We need to use both energy reach and precision measurements to push beyond the 1 TeV scale in our exploration. The quest for new physics will be thus conducted in a two-tier approach: 1) looking for indirect evidence of beyond-the-Standard-Model physics (BSM) through precision measurements of the properties of the Higgs boson and other SM particles, and 2) searching for direct evidence of BSM physics at the energy frontier, reaching multi-TeV scales.

The EF currently has a top-notch program with the LHC and the High Luminosity LHC (HL-LHC) at CERN, which sets the basis for the EF vision. **The EF supports continued strong US participation in the success of the LHC, and the HL-LHC construction, operations, computing and software, and most importantly in the physics research programs, including auxiliary experiments.**

The discussions on projects that extend the reach of the HL-LHC underlined that preparations for the next collider experiments have to start now to maintain and strengthen the vitality and motivation of the community. Colliders are the ultimate tool to carry out such a program thanks to the broad and complementary set of measurements and searches they enable. Several projects have been proposed such as ILC, CLIC, FCC-ee, CEPC, Cool Copper Collider (C^3) or HELEN for e^+e^- Higgs Factories, and CLIC

[†]deceased, Jan. 1, 2023.

at 3 TeV centre-of-mass energy, FCC-hh, SPPC and Muon Collider for multi-TeV colliders. For a detailed discussion of timeline, cost, challenges of those accelerator projects we refer to the Accelerator Frontier Integration Task-Force (ITF) report [1] and the appendix 6.A.3. Dedicated fora were established across frontiers to bring together diverse expertise in the study of future e^+e^- and $\mu^+\mu^-$ colliders. Results from their studies are available in their reports [2, 3] and have informed the studies presented in this report.

All proposed collider physics experiments need complex detectors as well as software and computing infrastructure, with cutting-edge technologies to meet their ambitious physics goals. The needs extend beyond generic R&D. Experience from R&D and building previous experiments informs us that it takes about 10 years from CD-0 (Critical Decision - 0) to the end of construction of a collider detector. For e^+e^- Higgs factories, immediate investment in targeted detector R&D is needed at a high priority to explore innovative new technologies and address specific detector challenges in preparation for technical designs. The schedule for multi-TeV colliders and their detectors is technically limited. Therefore for multi-TeV colliders, a long-term program to study the accelerator and detector challenges and reduce overall costs for construction is needed.

In summary, **the EF supports a fast start for construction of an e^+e^- Higgs factory (linear or circular), and a significant R&D program for multi-TeV colliders (hadron and muon). The realization of a Higgs factory will require an immediate, vigorous and targeted detector R&D program, while the study towards multi-TeV colliders will need significant and long-term investments in a broad spectrum of R&D programs for accelerators and detectors.** These projects have the potential to be transformative as they will push the boundaries of our knowledge by testing the limits of the SM, and indirectly or directly discovering new physics beyond the SM.

The US EF community has also expressed renewed interest and ambition to bring back energy-frontier collider physics to the US soil while maintaining its international collaborative partnerships and obligations.

The EF community proposes several parallel investigations over a time period of ten years or more for pursuing its most prominent scientific goals, namely 1) supporting the full (3 - 4.5 ab^{-1}) HL-LHC physics program, 2) proceeding with a Higgs factory, and 3) planning for multi-TeV colliders at the energy frontier.

The proposed plans in five year periods starting 2025 are given below.

For the five year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs factory detector R&D program,
3. Develop an initial design for a first stage TeV-scale Muon Collider in the US,
4. Support critical detector R&D towards EF multi-TeV colliders.

For the five year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support construction of an e^+e^- Higgs factory,
3. Demonstrate principal risk mitigation for a first stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for detector R&D for energy frontier multi-TeV colliders.

The EF community recognizes that its success critically depends on the resources obtained by the Accelerator Frontier (AF), as there is a direct linkage between the EF vision and advances in accelerator R&D. The EF community strongly supports the AF in its proposal to establish an e^+e^- Higgs factory program, and start R&D for energy frontier multi-TeV colliders with appropriate funding [4]. Moreover, the visibly strong interdependence between the EF and the Theory Frontier is key to the success of both frontiers, and EF supports a strong and well funded theory program [5]. Contributions from Instrumentation Frontier [6] and the Computational Frontiers [7] are key to the realization of the vision of the EF. In addition, the collaboration with the Community Engagement Frontier [8] as well as the cross-fertilization with other Frontiers such as the Rare Processes and Precision Measurements [9], Cosmic [10], and Neutrino Physics [11] Frontiers are important. Finally, to achieve its goal to advance the current and future scientific endeavors, the EF community has a renewed focus on building and advancing an inclusive workforce, with members from diverse backgrounds, expertise, and career levels.

The vision of the EF community is presented more extensively in Sec. 6.6, and is motivated by the physics studies that are summarized in Secs. 6.1 to 6.5. The appendices in Sec. 6.A discuss the technological developments that will enable the next generations of EF experiments, as well as opportunities and challenges for the EF community, in terms of collaborations, vibrancy, and diversity as well as needed investments. The estimated timelines and cost for the next generation of large-scale projects in the EF are also provided.

6.1 Big Questions in the Energy Frontier

After decades of pioneering explorations and milestone discoveries, the Standard Model (SM) of particle physics has been confirmed as the theory that describes electroweak (EW) and strong interactions up to energies of a few hundreds of GeV with great accuracy but it is also leaving some fundamental questions unexplained. In this context, the EF aims at advancing the investigation of some of the still open fundamental questions such as the evolution of the early universe, the matter-antimatter asymmetry of the universe, the nature of dark matter, the origin of neutrino masses, the origin of the EW scale, and the origin of flavor dynamics, with a broad and strongly motivated physics program that will push the exploration of particle physics to the TeV energy scale and beyond. Our sharply focused agenda includes in-depth studies of the SM as well as the exploration of physics beyond the SM to discover new particles and interactions. The vision of the EF must keep its focus on these *big questions*, and must provide opportunities to examine them from as many angles as possible, while also continuing to pursue the *exploration of the unknown*, a leading driver of the EF physics program. This is the core of the EF program as pictorially illustrated in Fig. 6-1.

Collider Physics offers a unique opportunity to study a huge number of phenomena and explore the connections between many of the fundamental questions we want to answer. The *big questions* outlined at the center of Fig. 6-1 unambiguously require new concepts beyond the SM of particle physics. A variety of processes can be used as *probes* (depicted as the smaller circles of Fig. 6-1) to discover and then characterize the nature of the BSM physics at play and energy-frontier colliders are instrumental to investigating such phenomena via numerous distinct *signatures* (listed as the outermost text in Fig. 6-1).

The multi-probe characteristic of high-energy colliders makes them a unique tool in the fundamental quest for answers to the core unknowns of particle physics. With a combined strategy of precision measurements

and high-energy exploration, future lepton colliders starting at energies as low as a few hundreds GeV up to a few TeV can shed substantial light on some of these key questions. Ultimately, it will be crucial to find a way to carry out experiments at higher energies, directly probing new physics at the 10 TeV energy scale and beyond.

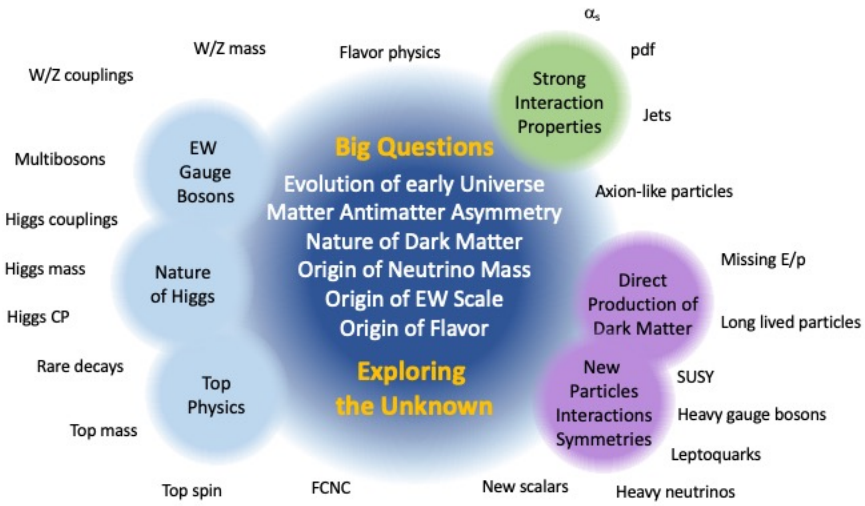


Figure 6-1. *Six categories of Probes and a multiple of Signatures accessible at energy-frontier colliders to address the Big Questions that are at the center of the EF pursuit.*

Within this big picture, the activities of the Snowmass 2021 EF has been structured around three main *probing* areas, broadly defined as EW Physics (Higgs-boson physics, top-quark and heavy-flavor physics, electroweak gauge bosons physics), Quantum Chromodynamics (QCD) and Strong Interactions (precision QCD, hadronic structure and forward QCD, heavy ions), and BSM physics (model-specific explorations, general explorations, dark matter at colliders), which have focused on three main key questions, as presented below.

1. What can we learn about the origin of the EW scale and the EW phase transition from an in-depth study of the the properties and interactions of SM particles?

   The 10^{th} anniversary of the discovery of the Higgs boson [12, 13], a tremendous achievement for our field, is being celebrated this year, 2022. This discovery provides the last piece of the SM puzzle and at the same time gives a unique connection to new physics beyond the SM that we need to exploit. The multitude of studies relating to precision Higgs-boson measurements (mass, width, couplings) may help uncover the nature of physics above the EW scale. Together with the full spectrum of EW, top-quark, and flavor-physics precision measurements, these studies will greatly improve the constraining power of global fits of fundamental parameters. The expected large number of Higgs-boson events may lead to measurements of the shape of the Higgs potential. The study of the Higgs boson, may also give us insight into flavor physics and vice versa. Last but not least, this study may lead us to understand the implications for naturalness.

2. What can we learn about the dynamics of strong interactions in different regimes ?

   The fundamental theory of strong interactions, QCD, plays a central role in the SM both as a confining gauge theory that can inspire a deeper understanding of quantum field theories, and at

the same time as a ubiquitous crucial component of all measurements at current and future hadron and lepton colliders. Answering the big questions ahead of us intrinsically depends on exploring and understanding the complex phenomenology of strong interactions in different regimes. To harvest the revolutionary progress witnessed in perturbative QCD calculations and Monte Carlo event generators during recent years, residual systematic uncertainties, from parton-shower effects to hadronization models, will have to be understood and reduced. New ideas to describe the dynamics that drives internal jet structure and their evolution as a function of energy will have to be explored. First-principle calculation of parton densities will have to be benchmarked. The upcoming era, featuring the HL-LHC, Belle II, the Electron-Ion Collider (EIC), new advances in theory including in lattice QCD, and potentially a Higgs factory promises to be a golden age for QCD.

3. How can we build a complete program of BSM searches which includes both model-specific and model-independent explorations?

   Models connect the high-level unanswered questions in particle physics (dark matter, EW naturalness, CP violation, etc) to specific phenomena, in a self-consistent way. They can be very predictive but model-dependent studies may fail to consider a broad range of new phenomena and search avenues. Many important questions need to be critically addressed. Which models should be considered and how can model parameter spaces be compared in a consistent way ? Can searches be conducted and interpreted in a model-agnostic way ? How can results from different experiments be compared in a model-independent way to ensure complementarity and avoid gaps in coverage ? Can future colliders chart new regions of model parameter space and also fill in gaps left by existing colliders ? What is the complementarity between precision measurements and direct searches ?

A detailed account of the work done by the EF Topical Groups in each of these areas is presented in a series of reports [14–18], highlights of which are illustrated in Secs. 6.3-6.5 of this report.

Finding answers generates more specific questions that will be considered in the studies presented in this report and will be an important factor in building a concrete vision for the future of particle physics explorations at the energy frontier. Among others, important aspects that have emerged as most relevant in determining future directions for the EF are the following: the theoretical motivation behind specific future directions, the potential of each future-collider proposal to provide substantial insights in answering the key questions identified as the focus of EF as well as the breadth and complementarity of their physics program, and the identification of what collider and detector developments are necessary to fully pursue the desired physics program of both precision measurements and searches for new physics.

The collider scenarios discussed in the following are summarized in Table 6-1 for Higgs factories and in Table 6-2 for multi-TeV colliders.

6.2 Addressing the Big Questions with EF Colliders

While the existence of BSM physics is well established by observational phenomena, and heavily suggested by theoretical considerations, the energy scale at which it will manifest and its characteristics, e.g. the couplings to known SM particles, are only indirectly constrained. For example Dark Matter (DM) may be a thermal weakly-interacting massive particle (WIMP) with possible extensions to the multi-TeV range, or it might have an extraordinarily low mass. Naturalness suggests that the mass scale of new physics should be close to the EW scale, but in concrete scenarios, such as supersymmetry, it can reach the 10 TeV scale or

Table 6-1. *Benchmark scenarios for Snowmass 2021 Higgs factory studies.*

Collider	Type	$\sqrt{s}$	$\mathcal{P}$[%] e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		2 M_{top}		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

Table 6-2. *Benchmark scenarios for Snowmass 2021 multi-TeV collider studies.*

Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}$[%] e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm 80/0$	2.5
		3.0	$\pm 80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

higher given the measured Higgs-boson mass. Furthermore it is quite possible that phenomena could show up unexpectedly at unpredicted scales as we have seen historically in our field.

Depending on the mass scale of new physics and the type of collider, the primary method for discovering new physics can vary. Investigation at the energy frontier allows one to combine direct BSM searches with precision measurements of observables sensitive to scales above the available center-of-mass energy. Furthermore, the type of collider and detectors that are employed will directly influence what signatures can be probed.

The fundamental lessons learned from the LHC thus far are that a Higgs-like particle exists at 125 GeV and there is no other obvious and unambiguous signal of BSM physics. This implies that either there is generically a gap to the scale of new physics, or new physics must be weakly coupled to the SM, or hidden in backgrounds at the LHC. The HL-LHC will either strengthen these conclusions further or potentially point us in a particular direction for discovery.

To understand how future colliders have complementary potential to unlock the mysteries around these fundamental questions beyond what the LHC and HL-LHC physics program can probe, it is illustrative to use a simplified picture as depicted in Fig. 6-2. We can imagine that generic new physics lives in a 2D parameter space governed by the coupling of new states to the SM and their mass scale. If the center-of-mass energy of a collider is above the one of the LHC, it can *directly* search for new states to higher mass scales. Higgs factories have smaller center-of-mass energies than the LHC, and therefore do not extend the *direct* mass reach beyond the LHC. However, by colliding leptons they offer significantly reduced backgrounds and

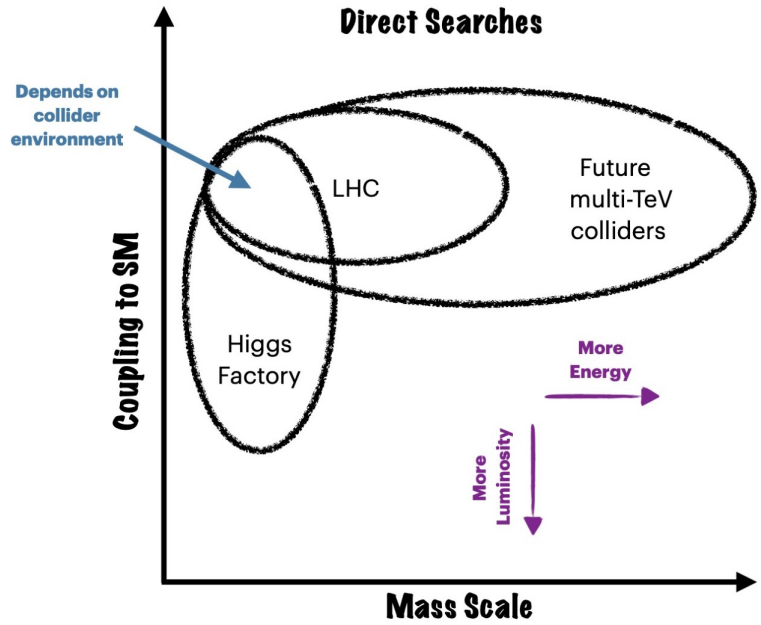


Figure 6-2. *The direct coverage of various colliders in the schematic space of coupling to the SM versus mass scale of BSM physics. "Higgs factory" and "multi-TeV colliders" correspond to a generic option among the ones listed in Table 6-1 and Table 6-2 respectively.*

the ability for triggerless readout, therefore they have the potential to probe new physics that is weakly coupled to the SM. Additionally, even in the overlap region of Higgs factories with the LHC, the former can be sensitive to new physics that is difficult to discriminate from backgrounds at the LHC.

Beyond the direct search for new physics, a key program for the EF is the precision measurement of SM predictions and parameters. Highly precise measurements allow the probing of scales above the kinematic limit for direct searches at colliders. This can be captured through Effective Field Theory (EFT) techniques when there is a gap between the probed energy scale and the scale of new physics. In EF studies, typically this is done by employing specific EFTs, e.g. SMEFT or the more general HEFT formalisms. If M is the mass scale of new physics and g_{BSM} is its generic coupling to the SM, then often deviations in SM parameters, η_{SM}, which occur from integrating heavy particles out at tree-level, scale at the leading order as

$$\delta\eta_{SM} \sim g_{BSM}^2 \frac{v^2}{M^2}, \tag{6.1}$$

for Higgs related parameters, where v is the vacuum expectation value of the Higgs, or in general as

$$\delta\eta_{SM} \sim g_{BSM}^2 \frac{E^2}{M^2}, \tag{6.2}$$

where it is assumed that the energy scale $E \ll M$ for the formalism to be applicable. If new physics only creates loop level deviations in a SM observable, then one can insert a loop factor $\sim 1/16\pi^2$ into Eqns. 6.1 and 6.2. Therefore depending on the precision achievable, as seen in Eqns. 6.1 and 6.2, mass scales larger than the direct reach can be probed. We can then overlay these types of indirect collider searches, particularly relevant for Higgs factories in Table 6-1, on our schematic space of BSM physics shown in Fig. 6-2, as explicitely illustrated in Fig. 6-3. As can be seen in Fig. 6-3 the energy versus precision trade-off *crucially* depends on the precision attainable. Suggestively, we have shown a 1% precision often associated with parameter measurements (except for e.g. the HZZ coupling at Higgs factories), where the scaling

typically does not extend beyond the LHC without invoking strong coupling. However, for quantities that are measured significantly more precisely, e.g. $\lesssim 0.1\%$, at future Higgs-factory programs, such as M_W, the reach can extend much further. This exact scaling in mass reach depends on the type of BSM physics, and both Higgs parameters and EW observables measured at Higgs factories are important for understanding complementary measurements available at future multi-TeV colliders. The precision that can ultimately be reached and in what types of observables strongly motivates advances in detector technology, increases in luminosity, use of polarization at lepton colliders, and improved theoretical calculations. Moreover depending on the type of collider, for example at a multi-TeV collider, the dichotomy between precision reach and energy reach can potentially be bridged with the availability of large statistics for processes as e.g. Higgs production *if* the environment can be fully controlled.

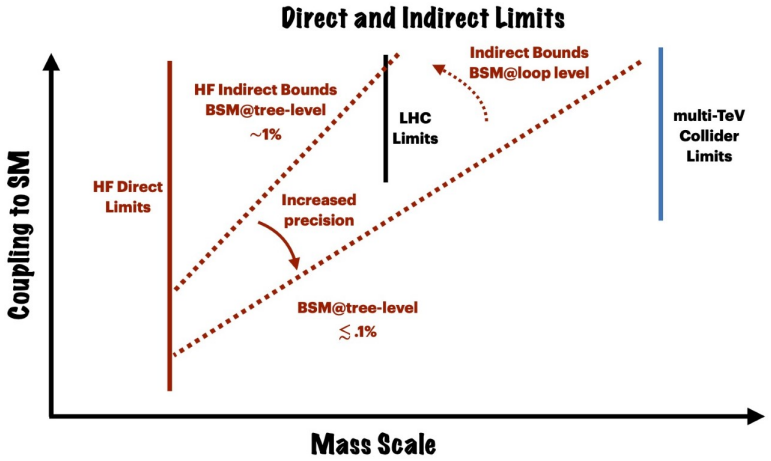


Figure 6-3. *Kinematic reach of direct and indirect searches in the same coupling-mass plane as in Fig. 6-2. The solid lines illustrate direct search limits while the dashed lines represent indirect limits. Higgs Factories (HF) can provide increased reach through indirect searches, benefiting from high-precision measurements. A 1% precision measurement suggests a probed scale of up to a few TeV in perturbative ultra-violet completion models if BSM physics couples at tree-level to the observables of interest. For illustration the potential LHC limit is also depicted. If new physics couples at loop-level then the scale probed indirectly is lower. The ultimate precision, and what scale the multi-TeV colliders can probe is collider specific.*

There can be a multitude of phenomena studied at low masses, incompatible with the EFT framework at those energies, that benefit from a reduced background environment at an e^+e^- Higgs factory. Additionally, even *within* one collider, precision measurements and direct searches coexist and offer multiple complementary probes. To move beyond scaling it is useful to give a few examples of how direct and indirect complementarity play out within the EF, as well as what are potential BSM features at low energy that the LHC may be missing. The remaining of the EF report and the EF Topical Group reports [14–18] will provide examples and more details, but we list a few illustrative ones here below.

- Higgs couplings and mass reach: the Higgs boson as the primary target for all future EF colliders provides many examples of the interplay of direct and indirect searches. For example in Two-Higgs Doublet Models, indirect Higgs-boson precision measurements can be complemented by direct resonance searches, EW precision, flavor physics and beyond. Numerous cases are discussed in Section 6.3.1 and in the corresponding Topical Group report [14].

- Supersymmetry is still a leading example of BSM physics, and while it is a canonical example of direct searches it also can be tested indirectly in numerous ways [18]. However as shown in Section 6.5.2 for

pMSSM parameter scans, indirect searches at Higgs factories do not exceed the typical region covered by the HL-LHC. Further examples can be found in several of the EF Topical Group reports [14, 18].

- The search for anomalous Trilinear Gauge Couplings (aTGC) and anomalous Quartic Gauge Couplings (aQGC) offer a particularly interesting example of the interplay of several search strategies and measurements [16]. At lowest dimension in the SMEFT expansion, deviations are only possible from BSM physics at loop level from new EW charged states. Therefore in addition to indirect multiboson measurements, direct searches for charged particles, which generate the effects, are powerful probes. These can include long-lived particle searches in the degenerate mass limit, or more canonical direct searches that can also be complemented by precision measurements of Higgs-boson properties when the splitting becomes larger. Furthermore there are multiple ways to search for vector boson scattering such as in ultraperipheral heavy-ion collisions, as discussed in Section 6.4.5 and in Ref. [17].

- Higgs-to-invisible decays is an example of where there can be "holes" in the LHC coverage even at low mass scales. A similar consideration can be made for precision measurements of Higgs-boson decays into light quark flavors which are difficult to detect at the LHC despite being copiously produced. These are both further discussed in Section 6.3.1 and in the corresponding Topical Group report [14].

In summary, EF colliders are the ultimate tool we possess to clarify the fundamental nature of deviations observed either at collider experiments or at low-energy experiments, thanks to their vast and unique physics programs.

The current landscape also provides notable examples of deviations in precision measurements of SM parameters that are currently under scrutiny by the particle physics community, and that can provide targets for direct BSM searches. Most notably, anomalies in (semi)leptonic B-hadrons decay, including hints of lepton flavor universality violations, the muon anomalous magnetic moment ($g_\mu - 2$), and the recent W-mass measurement might develop into unambiguous BSM signals that call for direct exploration to clarify their nature. Regardless the nature of the present and future anomalies, such occurrences call for a flexible EF program that can develop and deploy a collider able to directly and unambiguously probe energy scales of the order of several TeV.

6.3 Electroweak Sector of the Standard Model

The investigation of EW interactions has played a crucial role in defining the SM, predicting all its bosonic and fermionic constituents, and guiding to their discovery over the last several decades. The discovery of the Higgs boson has provided the last piece of evidence to establish the SM as a well-defined quantum field theory and confirm its predictions, but it has also left unanswered more fundamental questions on the nature of this particle, its relation to defining the EW scale via the spontaneous breaking of the EW symmetry, as well as its role in the origin of fermion masses and flavor dynamics. Hence, focused precision studies of the properties of EW physics still offer a unique handle to indirectly probe the kind of fundamental new physics that could explain the origin of the EW scale and relate it to some of the big open questions we outlined in Sec. 6.1.

The LHC and HL-LHC will continue exploring EW interactions at the Energy Frontier with a broad program of measurements of Higgs-boson, EW gauge-boson (W, Z), and heavy-fermions (t, b, and also c quark) properties and interactions. Future colliders, both Higgs Factories and multi-TeV colliders, will push the precision of such measurements to indirectly constrain effects of new physics in the 10 TeV range or above and, at the highest energies, provide direct access to such physics. In this section we review the current

status, future projections, and overall reach of EW physics studies articulated into three sections on Higgs-boson physics (Sec. 6.3.1), top-quark and heavy-flavor physics (Sec. 6.3.2), and EW gauge-boson physics (Sec. 6.3.3). The current and future constraining power of global fits of EW observables in the SM effective field theory is presented in Sec. 6.3.4.2.

6.3.1 Higgs and BSM physics

Over the past decade the LHC has fundamentally changed the landscape of high energy particle physics through the discovery of the Higgs boson and the first measurements of many of its properties. As a result of this, and no other "discoveries" at the LHC, the questions surrounding the Higgs boson have only become sharper and more pressing for planning the future of particle physics.

The SM is an extremely successful description of nature, with a basic structure dictated by symmetry. Still, symmetry alone is not sufficient to fully describe the microscopic world we explore, and even after specifying the gauge and space-time symmetries, and number of generations, there are still 19 parameters undetermined by the SM (not including neutrino masses). Out of these parameters 4 are intrinsic to the gauge theory description, the gauge couplings and QCD theta angle. The other 15 parameters are intrinsic to the Higgs sector or how other SM particles couple to the Higgs, illustrating its paramount importance in the SM. In particular, the masses of all fundamental particles, their mixing, CP violation, and the basic vacuum structure are not predicted from symmetry principles of the SM and need to be derived from experimental data to test the consistency of the SM itself. However, the centrality of the Higgs boson goes far beyond just dictating the parameters of the SM.

The Higgs boson is connected to some of our most fundamental questions about the Universe. Its most basic role in the SM is to provide a source of Electroweak Symmetry Breaking (EWSB). This effect can be formulated via the Higgs potential in the following way:

$$V(H) = -\mu^2(H^\dagger H) + \lambda(H^\dagger H)^2 \,. \tag{6.3}$$

Indeed, if the mass parameter in the potential (the term quadratic in the SM complex scalar doublet H) simply had a positive sign rather than negative, there would be no EWSB and our universe would not exist in its current form. The explanations of *why* EWSB occurs and the presence of such a minus sign are outside the realm of the SM Higgs boson. In other examples of spontaneous symmetry breaking that we have seen manifest in our universe described by Quantum Field Theory (QFT), there has been a dynamical origin. In principle the Higgs could be a composite of some other strongly coupled dynamics, as we have seen before in history for other particles. Alternatively, the Higgs could be a fundamental scalar and EWSB could arise dynamically through its interactions with other BSM fields. It is even possible that there could be dynamical connections to cosmology or the anthropic principle. No matter what the origin of EWSB is, it will leave imprints on the properties of the SM Higgs boson itself. Moreover, answers to questions such as "*Is the Higgs boson composite or fundamental?*" can have ramifications far beyond just the origin of EWSB.

If the Higgs boson is a fundamental particle, it represents the first fundamental scalar particle discovered in nature. This has profound consequences both theoretically and experimentally. From our modern understanding of QFT, fundamental scalars should not exist in the low energy spectrum without an UV-sensitive fine tuning if the SM is an EFT of some more fundamental theory. This is known as the naturalness or hierarchy problem. From studying properties of the Higgs boson, one can hope to learn whether there is some larger symmetry principle at work stabilizing the spectrum. For example supersymmetry, neutral naturalness, or if the correct theory is a composite Higgs model, the Higgs could be a pseudo-Goldstone boson.

Experimentally there are also a number of intriguing directions that open up if the Higgs boson is a fundamental particle. The most straightforward question is whether the Higgs boson is a unique scalar field in our universe, or is it just the first of many. Additional scalars can always couple to the Higgs at the renormalizable level, and depending on their symmetry properties they can couple to gauge bosons or fermions as well (e.g. the more commonly known Two Higgs Doublet Models). What this implies is that if the Higgs is not unique, there are two complementary methods for investigating this: searching directly for these new scalar states, or measuring their indirect effects on the SM Higgs-boson properties. Also related to the fact that new scalars can always leave imprints on the Higgs is that a fundamental Higgs particle is special in QFT. Using only the SM Higgs field, one can construct the lowest-dimension gauge- and Lorentz-invariant operator in the SM. This means that generically if there are 'Hidden" sectors beyond the SM sector (perhaps related to DM), the Higgs boson is the most relevant portal to these sectors, often referred to as the "Higgs Portal". Whether these new sectors have a mass scale well below or above the scale of EWSB implies drastically different experimental observables. For light new sectors of the universe, this can manifests itself as exotic Higgs decays, invisible Higgs decays, and shifts in the Higgs total width, as can be probed well at e^+e^- colliders. For heavier hidden sectors, the observables are different and the highest energy collider options are needed.

Another aspect of determining if the Higgs is a fundamental scalar particle concerns whether the minimal Higgs potential is correct. If there are new BSM particles that couple to the Higgs, the potential itself can receive modifications. This is not solely a question about the potential, because its form has repercussions for both our understanding of the early universe and its ultimate fate. For the early universe, the SM predicts that the electroweak symmetry should be restored at high temperatures. However, depending on the actual form of the potential the question remains as to whether there even was a phase transition let alone its strength. Additionally, depending on its form, the Higgs potential can control the future of our universe as our vacuum may be metastable. Furthermore a strong EW first order phase transition can have implications for Baryogenesis as well.

Finally, the Higgs boson is connected to some of the most puzzling questions in the universe: flavor, mass, and CP violation. There are effectively two types of interactions in the SM, gauge interactions and Higgs interactions. Gauge interactions are tightly constrained and do not fundamentally differentiate flavor. Higgs interactions govern all the important quantities for flavor, mass, and CP violation in the SM. In particular, all problems connected with flavor and CP – the origin of fermion masses, the origin of neutrino masses, the origin of the neutrino mixing matrix and CKM angles – ultimately require knowledge of the fundamental nature of the Higgs sector. Otherwise, we are just fitting parameters without an understanding. The full information that we need is only available at high energy by studying the Higgs boson.

The fact that understanding the properties of the SM Higgs boson connects to so many fundamental questions illustrates how central it is to the HEP program. The connections briefly reviewed so far obviously can each be expanded in greater detail, but to collect the various themes in a simple-to-digest manner they are illustrated in Fig. 6-4 and examples of the interplay between experimental observables and fundamental questions are given in Fig. 6-5. The generality of the concepts and questions posed in Fig. 6-4 could even belie connections to additional fundamental mysteries. For example, the Higgs portal could specifically connect to DM or other cosmological mysteries.

6.3.1.1 Higgs present and future

The LHC Run 2 with about 140 fb^{-1} of data analyzed is providing a wealth of new measurements for the Higgs sector. The most recent Higgs-boson mass measurements, from CMS and ATLAS, set its value to be 125.38±0.14 GeV [19] and 124.92±0.21 GeV [20] respectively, using both the diphoton and ZZ decay

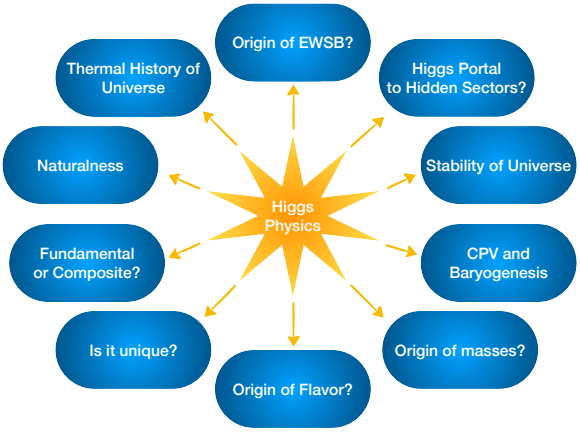


Figure 6-4. *The Higgs boson as the keystone of the Standard Model is connected to numerous fundamental questions that can be investigated by studying it in detail through the many experimental probes illustrated in Fig. 6-5.*

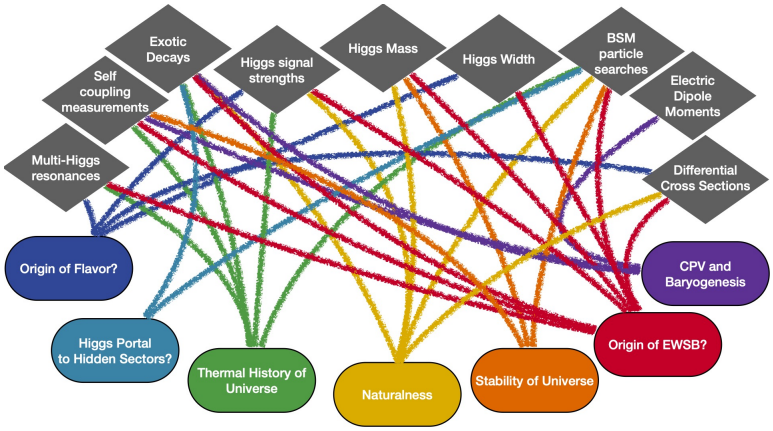


Figure 6-5. *Examples of the interplay between experimental observables and fundamental questions connected to the Higgs boson.*

channels. The Higgs-boson mass is a free parameter in the SM and it is now known to per-mille accuracy. We are entering the era of precision Higgs physics, with some of the Higgs-boson couplings measurements approaching $\mathcal{O}$(5-10)% precision. All the major production mechanisms of the SM Higgs boson (h) have been observed at the LHC: gluon fusion (ggF), vector-boson fusion (VBF), the associated production with a W or Z boson (Wh, Zh), and the associated production with top quarks ($t\bar{t}h$, th). All of these channels are precisely measured, with the experimental sensitivity of some modes nearing the precision of state-of-the-art theory predictions. Further details of the current LHC measurements at ATLAS and CMS are contained within the Higgs-physics Topical Group report [14].

A simultaneous fit of many individual production rate times branching-fraction measurements is performed to determine the values of the Higgs-boson coupling strength. The κ-framework defines a set of parameters (κ_X for $X = W, Z, \ldots$) that affect the Higgs-boson coupling strengths without altering the shape of any kinematic distributions of a given process. SM values ($\kappa_X = 1$) are assumed for the coupling strength modifiers of first-generation fermions, the other coupling strength modifiers are treated independently. The results are shown in Fig. 6-6 for ATLAS and CMS. In this particular fit, the presence of non-SM particles in the loop-induced

processes is parameterized by introducing additional modifiers for the effective coupling of the Higgs boson to gluons, photons and $Z\gamma$, instead of propagating modifications of the SM-particle couplings through the loop calculations. In these results, it is also assumed that any potential effect beyond the SM does not substantially affect the kinematic properties of the Higgs boson decay products. The coupling modifiers are probed at a level of uncertainty of 10%, except for κ_b and κ_μ ($\approx 20\%$), and $\kappa_{Z\gamma}$ ($\approx 40\%$). Notably absent are couplings to light fermions, many of whose SM values are out of reach for a LHC measurement (i.e the up, down, strange, charm, and electron couplings) but further details may be found in the Higgs-physics Topical Group report [14].

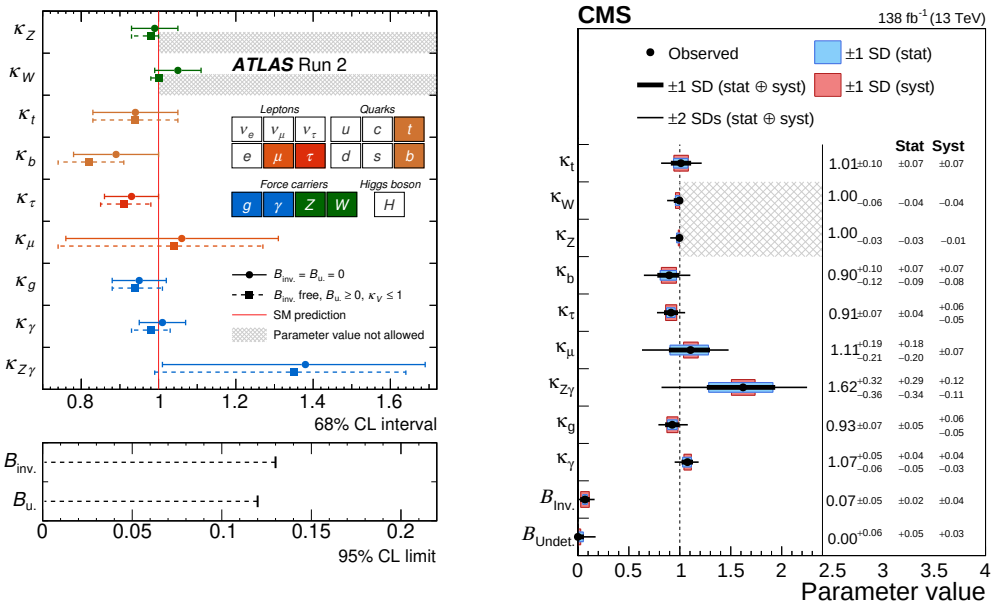


Figure 6-6. *Left, ATLAS best-fit values and uncertainties for Higgs-boson coupling modifiers per particle type with effective photon and gluon couplings, the branching fraction to invisible (B_i), and undetected decays (B_u) included as free parameters, and the measurement of the Higgs-boson decay rate to invisible final states included in the combination [21]. Right, CMS summary of the Higgs-boson couplings modifier best fit. The thick (thin) black lines report the 1σ (2σ) confidence intervals [22].*

The scalar potential of the SM responsible for the EWSB mechanism, is currently still very far from being probed. After EWSB, the SM scalar potential (see Eq. 6.3) gives rise to cubic and quartic terms in the Higgs-boson field, induced by the self-coupling term (λ). Within the SM, the Higgs-boson self-coupling is fully predicted in terms of the Fermi coupling constant and the Higgs-boson mass, which has been measured at per-mille level accuracy by the ATLAS and CMS experiments [19,20]. The Higgs self-coupling is accessible through Higgs-boson pair production (hh) and inferred from radiative corrections to single-Higgs production measurements. Measuring this coupling is essential to shed light on the structure of the Higgs potential, whose exact shape can have deep theoretical consequences.

The maximum value of the acceptance for the $gg \to hh$ process is obtained for $\kappa_\lambda \sim 2$, where the cross section is at a minimum. Here κ_λ refers to the ratio of the measured value to the predicted SM value of the Higgs self coupling and must be unity if the SM is a complete theory. Measuring $\kappa_\lambda \neq 1$ would unambiguously imply that there is some new physics beyond the SM. The corresponding intervals where κ_λ is observed (expected) to be constrained at 95% CL are listed in Table 6-3 for the main channels.

Final state	Collaboration	allowed κ_λ interval at 95% CL	
		observed	expected
$b\bar{b}b\bar{b}$	ATLAS	-3.5 – 11.3	-5.4 – 11.4
	CMS	-2.3 – 9.4	-5.0 – 12.0
$b\bar{b}\tau\tau$	ATLAS	-2.4 – 9.2	-2.0 – 9.0
	CMS	-1.7 – 8.7	-2.9 – 9.8
$b\bar{b}\gamma\gamma$	ATLAS	-1.6 – 6.7	-2.4 – 7.7
	CMS	-3.3 – 8.5	-2.5 – 8.2
comb	ATLAS	-0.6 – 6.6	-1.0 – 7.1
	CMS	-1.2 – 6.8	-0.9 – 7.1

Table 6-3. *The observed and expected 95% CL intervals on κ_λ for the most sensitive individual final states analyzed for non-resonant hh production at 13 TeV with about 126-139 fb^{-1} under the assumption of no hh production. All other Higgs boson couplings are set to their SM values. Constraints derived under different statistical assumptions are also available in [22–28].*

The planned HL-LHC, starting in 2029[1] will extend the LHC dataset by a factor of $\mathcal{O}(10)$, and produce about 170 million Higgs bosons and 120 thousand Higgs-boson pairs. This would allow an increase in the precision for most of the Higgs-boson couplings measurements. The HL-LHC will dramatically expand the physics reach for Higgs physics. Current projections are based on Run 2 results and some basic assumptions that some of the systematic uncertainties will scale with luminosity and that improved reconstruction and analysis techniques will be able to mitigate pileup effects. The studies also assume that the theory uncertainty is reduced by a factor of 2 relative to current values. Studies based on the 3000 fb^{-1} HL-LHC dataset estimate that we could achieve $\mathcal{O}(2-4\%)$ precision on the couplings to W, Z, and third generation fermions. But the couplings to u, d, and s quarks will still not be accessible at the LHC directly, while the charm-quark Yukawa is projected to be directly constrained to $\kappa_c < 1.75$ at the 95% CL [30]. The Higgs-boson self coupling is a prime target of the HL-LHC and current rough projections claim the trilinear self-coupling will be probed with $\mathcal{O}(50\%)$ precision. We will be able to exclude the hypothesis corresponding to the absence of self-coupling at the 95% CL in these projections for HL-LHC, but not to test the SM prediction [30].

Future colliders are charged with the challenging tasks of testing the SM predictions of the Higgs-boson Yukawa couplings to light-flavor quarks, and improving the precision on the LHC Higgs-coupling measurements. An e^+e^- Higgs factory or Muon Collider can measure these couplings with smaller uncertainties than the HL-LHC due to a combination of knowing the momentum of the incoming particles more precisely, smaller background environments, and better detector resolutions. Indeed, at an e^+e^- Higgs factory the precision can be enhanced by the availability of precise calculations combined with much more democratic production rates: Higgs production is roughly of the same order as other processes in e^+e^- collisions, whereas the LHC must trigger and select Higgs events among backgrounds that are multiple orders of magnitude larger. Moreover, tagging of charm and strange quarks, as previously demonstrated at SLC/LEP, gives effective probes for precision measurements of charm- and strange-quark Yukawa couplings. The cleaner e^+e^- environment aided by beam polarization could become a sensitive probe to reveal more subtle phenomena [31]. For high-energy Muon Colliders, the primary driver is the cleaner environment plus increased statistics [32]. The measurement of the Higgs self-coupling demands access to high-energy center-of-mass collisions to benefit from the larger dataset of hh pairs and is a major goal of all future colliders.

[1] This refers to the updated schedule presented in January 2022 [29]

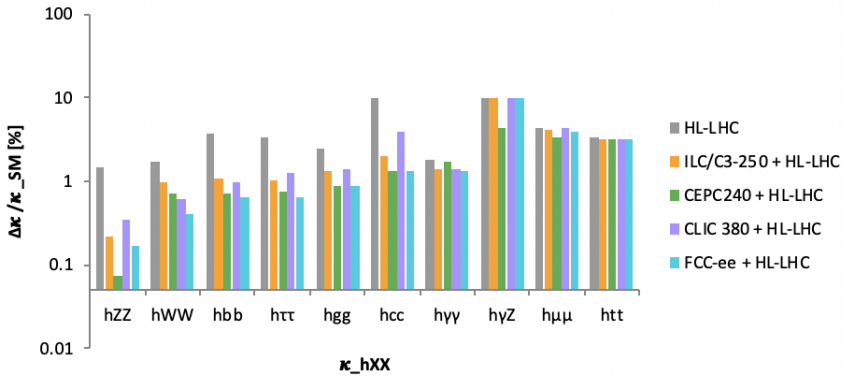


Figure 6-7. *Projected relative Higgs-coupling measurements in % when combined with HL-LHC results. All values assume no BSM decay modes. In addition, only the following collider stages are shown: 3 ab^{-1} and two interaction points (IPs), ATLAS and CMS, for the HL-LHC at 14 TeV, 2 ab^{-1} and 1 IP at 250 GeV for ILC/C^3, 20 ab^{-1} and 2 IP at 240 GeV for CEPC, 1 ab^{-1} and 1 IP at 380 GeV for CLIC, and 5 ab^{-1} and 4 IPs at 240 GeV for FCC-ee. Note that the HL-LHC κ_{hcc} projection uses only the CMS detector and is an upper bound [30].*

While all future colliders give strong contributions to the Higgs precision program, the first stages of e^+e^- Higgs factories are particularly compelling since they can all be constructed in the near future if funding is available, while other collider options require significantly more R&D. Studies for the five current e^+e^- Higgs factory proposals—ILC [33], C^3 [31], CEPC [34], CLIC [35], and FCC-ee [36]—demonstrate that experiments at these facilities can achieve high precision. Despite their different strategies, all these proposals lead to very similar projected uncertainties on the Higgs-boson couplings when the colliders are run at the same energies. The higher luminosity proposed for circular e^+e^- colliders is compensated by the advantages of polarization at linear colliders, yielding very similar projected sensitivity for the precision of Higgs couplings [37,38].

We show the projected sensitivity for the first stages of proposed e^+e^- colliders combined with HL-LHC projections in Fig. 6-7. These results are done in the so-called "kappa-0" framework, which does not allow for BSM decays of the Higgs boson, and are then combined with projections for results from HL-LHC. It is clear that the dominant improvement from HL-LHC results is in the couplings to b's, c's, and $\tau's$, along with extremely precise measurements of the Higgs interactions with W and Z bosons. The future lepton colliders not only can significantly improve on the knowledge of the coupling to the charm quark, but potentially also the coupling to the strange quark, with possible future detector advances, and may even set relevant direct bounds on Higgs couplings to up and down quarks. A dedicated run at the Higgs pole by the FCC-ee has the possibility to measure the coupling of the Higgs to electrons, which would be an important verification of the SM. Therefore there are subtle differences in the various e^+e^- Higgs factories and in some cases further study is needed to understand how real the differences are.

Measuring the Higgs couplings can be viewed as part of a global program of fitting to BSM physics in the EFT framework. In this approach, Higgs interactions are connected to processes without Higgs bosons through the EFT operators, the so-called "Higgs without Higgs" events. The κ framework, where the kinematic structure of the Higgs interactions is assumed to be identical to the SM, can be seen as a simplified metric for understanding the capabilities of future colliders for Higgs studies alone, and the only possibility when BSM physics affects Higgs properties at scales not validly described by an EFT approach. In these cases a combination of κ fits and other observables can be more useful. The dedicated EFT analysis shown in Section 6.3.4.2 combines information from the Higgs sector with information from precision

EW measurements, diboson production, and top-quark measurements, including kinematic information, to attempt to gain a deeper understanding of the underlying physics.

Beyond couplings to fermions and gauge bosons, the HL-LHC can constrain the Higgs boson width indirectly from the $ZZ \to 4$ lepton channel, with a projected measurement of $\Gamma_h = 4.1^{+.7}_{-.8}$ MeV, corresponding to roughly a 17% accuracy [30]. The indirect measurement of the Higgs-boson width can be sensitive to the assumption that there is no new BSM physics contributing to the width. However, it is more akin to an absolute coupling normalization and can be viewed as part of the larger "Higgs without Higgs" framework. BSM physics that invalidates these measurements is not generic, but further complementary information from other colliders is desired.

One distinct advantage of the lepton colliders is the possibility to obtain extremely precise and relatively model-independent measurements of the Higgs boson width. The measurement of the width can confirm the SM prediction given that it can be very sensitive to the scale of new physics. The fully reconstructed Z boson in the final state along with the well determined 4-momenta of the initial state leptons in the Zh process allows for a clean determination of the Higgs-boson kinematics regardless of the Higgs decay channel. The full FCC-ee program (combined with HL-LHC) allows for a 1% measurement of the Higgs-boson width. Using a SMEFT fit, the ILC finds similar results for the full program, but with just the initial 250 GeV run, a 2% measurement on the total width can be obtained. A Muon Collider running at $\sqrt{s} = 125$ GeV can obtain a model independent measurement of the Higgs-boson width at the 68% level of 2.7% (1.7%) with 5 fb^{-1}(20 fb^{-1}) by using a line-shape measurement [39]. A high-energy Muon Collider should obtain a similar order of magnitude precision using the indirect methods employed at the LHC with the same theoretical assumptions, and the FCC-hh could in principle also use these methods with further study.

collider	Indirect-h	hh	combined
HL-LHC [40]	100-200%	50%	50%
$\text{ILC}_{250}/\text{C}^3$-250 [31,33]	49%	–	49%
$\text{ILC}_{500}/\text{C}^3$-550 [31,33]	38%	20%	20%
$\text{ILC}_{1000}/\text{C}^3$-1000 [31,33]	36%	10%	10%
CLIC_{380} [35]	50%	–	50%
CLIC_{1500} [35]	49%	36%	29%
CLIC_{3000} [35]	49%	9%	9%
FCC-ee [36]	33%	–	33%
FCC-ee (4 IPs) [36]	24%	–	24%
FCC-hh [41]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [39]	-	15-30%	15-30%
μ(10 TeV) [39]	-	4%	4%

Table 6-4. *Sensitivity at 68% probability on the Higgs cubic self-coupling at the various future colliders. Values for the indirect single Higgs determinations below the first line are taken from [42]. The values quoted here are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.*

A measurement of the Higgs self-coupling is out of reach of Run 3 of the LHC and requires either a larger dataset, or/and a higher collision energy. The self coupling can be measured by the direct production of hh pairs, or inferred indirectly through the contribution of the Higgs self-coupling to loop corrections to the single-Higgs rate. However, for the indirect measurement to be relevant, it requires that new physics contributions dominate only the triple Higgs coupling shift. While this can naively be accounted for in a SMEFT fit, in realistic models this is much more difficult [43].

The projected sensitivities to the Higg-boson self-coupling at the various future colliders are presented in Table 6-4. These correspond to projections for a single experiment except for the 'combined' results which for the HL-LHC correspond to the combined projections of ATLAS and CMS experiments. We see that this is an extremely challenging measurement at all colliders. Since the measurement is limited by the small number of hh events, the measurement improves with the higher energy colliders. The indirect measurement improves with the luminosity of the lepton colliders since it is extracted from single-Higgs production. In principle measurements at different center of mass energies can be used to disentangle the indirect effects of shifts in the triple Higgs couplings, however it also depends on the assumptions of what types of other operators can contribute.

The ATLAS and CMS experiments have determined that the observed 125-GeV mass boson has the Higgs boson quantum numbers $j^{PC} = 0^{++}$. Small violations of CP symmetry in the hVV ($V = W, Z$) and $hf\overline{f}$ couplings are still allowed and are an important target of future experimental measurements. Hadron colliders provide essentially the full spectrum of possible measurements sensitive to CP violation in the Higgs boson interactions. Most processes other than the Higgs gluon interactions could be studied at an e^+e^- collider, especially with the beam energy above the $t\bar{t}h$ threshold. Future e^+e^- colliders are expected to provide comparable sensitivity to HL-LHC in $hf\overline{f}$ couplings, and potentially higher sensitivity in hZZ couplings. A Muon Collider operating at the Higgs boson pole allows to measure the CP structure of the $h\mu\mu$ vertex with the beam polarization.

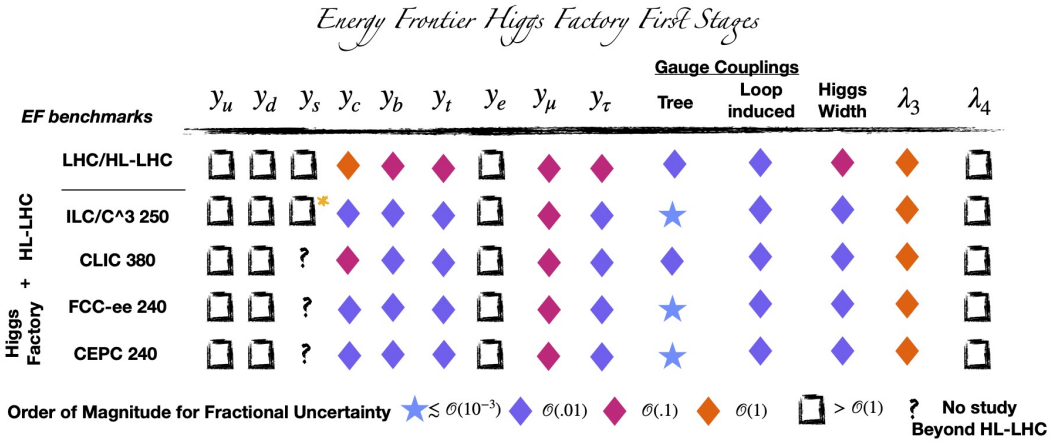


Figure 6-8. *A snapshot of future Higgs precision measurements of SM quantities based on the order of magnitude for the fractional uncertainties with the range defined through the geometric mean. In this figure the first stages of each e^+e^- Higgs factory are shown in combination with the Hl-LHC, as well as the HL-LHC separately. The Higgs factories are defined as those listed in Section 6.2 of the EF Report, excluding the 125 GeV Muon Collider whose timescale is in principle longer term. The specific precision associated to each coupling can be found in the Higgs-physics Topical Group report [14] and references therein. A * is put on the ILC measurements for the strange-quark Yukawa coupling to single it out as a new measurement proposed during Snowmass 2021, and is shown in Fig 6-13. The ? symbol is used in the case where an official study has not yet been performed, for example in the case of strange tagging for CLIC, FCC-ee, and CEPC. This does not mean that they cannot achieve a similar precision, but it is yet to be demonstrated whether based on their detector concepts the measurements is worse or can be improved.*

We have presented an overview of the types of precision measurements of Higgs-boson properties that can be done at future colliders, specific numbers for certain observables at all colliders have been shown, and general coupling fits in the case of the first-stage e^+e^- Higgs factories were shown in Fig. 6-7. However, it is important to understand that there are more observables than discussed here and to consider how high-energy colliders fit into the Higgs precision program. A comprehensive study is presented in the Higgs-

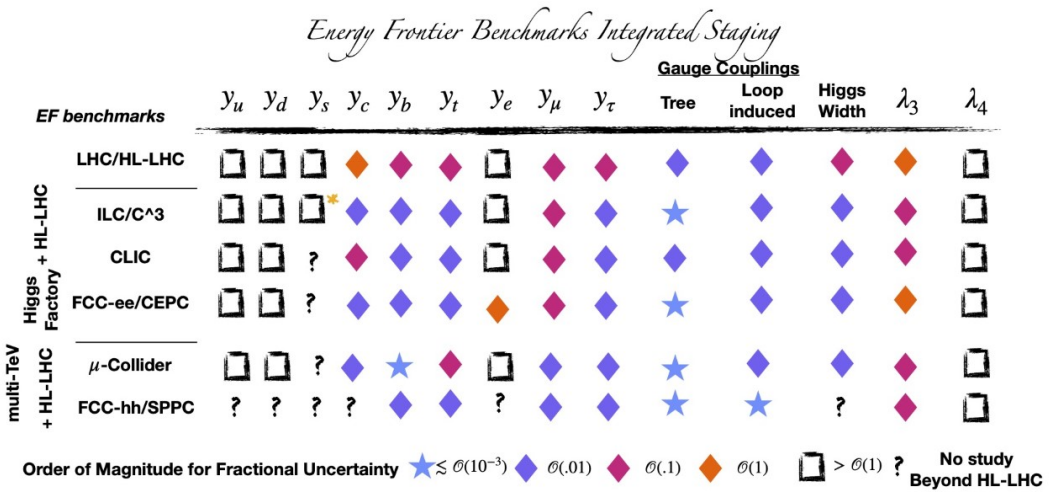


Figure 6-9. *A snapshot of future Higgs precision measurements of SM quantities based on the order of magnitude for the fractional uncertainties with the range defined through the geometric mean. In this figure the ultimate reach of the final stages of all Higgs factories and multi-TeV colliders are shown in combination with the HL-LHC results, as well as the HL-LHC separately. All benchmarks and stages are defined in Section 6.2 of the Energy Frontier Report. The specific precision associated to each coupling can be found in the Higgs-physics Topical Group report [14] and references therein. A * is put on the ILC measurements for the strange-quark Yukawa coupling to single it out as a new measurement proposed during Snowmass 2021, and shown in Fig 6-13. The ? symbol is used in the case where an official study has not yet been performed. It does not connotate that a given collider should be worse than similar ones, but simply that whether it is better or worse based on detector design has not been demonstrated.*

physics Topical Group report [14]. However, instead of displaying all info as a large table or bar chart, we will conclude this section by displaying a quantitative coarse grained version of all Higgs precision results in Fig. 6-8 and Fig. 6-9. As can be seen in Fig. 6-7 and Fig. 6-8, all first-stage Higgs factories have a very similar reach. However, it also emphasizes that there are still a large number of missing pieces to the Higgs puzzle after only first-stage Higgs factories. In Fig. 6-9, all stages of future colliders that are discussed in Section 6.2, are combined with the HL-LHC. As we see in this coarse graining, all colliders are compelling, and there is significant progress through Higgs factories and multi-TeV collider proposals compared to the HL-LHC program. In particular with the additional stages we start to see differences in the various proposed collider programs for Higgs physics. Linear e^+e^- colliders begin to demonstrate advantages especially in the measurement of the Higgs self coupling compared to circular e^+e^- colliders, whereas the circular colliders can potentially measure the electron Yukawa coupling. Furthermore, multi-TeV colliders such as the Muon Collider or FCC-hh extend the knowledge of the Higgs boson even further, albeit on different timescales. However, despite the enormous progress we expect from the currently proposed future colliders in testing the SM Higgs boson sector with high precision, the research for further improvements will have to continue. More specifically, the measurements of certain couplings, e.g. the light-quark Yukawas or the quartic self-coupling of the Higgs boson, that are challenging at the future colliders proposed in the Snowmass 2021 proceedings, motivate a continuing research and development.

6.3.1.2 What can we learn about BSM physics from Higgs physics

The ultimate goal of precision Higgs physics is to learn about new physics at high scales, or to find portals to new physics that could be present at the EW scale or below. As discussed earlier from an EFT context, the generic scale associated with precision Higgs physics at future colliders typically extends up to a few TeV.

To go further requires the understanding of the interplay between UV models and Higgs physics. Given that the mapping of fundamental physics questions to Higgs direct and indirect observables is difficult to fully organize comprehensively, the topical report instead focused on specific types of models and observables: Higgs Singlets, Higgs Doublets (including Flavor), Loop-level deviations, and Higgs Exotic Decays. Fundamental questions of course can be related to all of these types of models and is done so in the Higgs-physics Topical Group report [14]. Other connections to fundamental questions are also emphasized in other parts of the EF report, for example whether the Higgs boson is an elementary or composite particle is investigated in Section 6.5.1.

Given that many of the model-dependent topics have been covered extensively for years, we first wish to highlight some of the results that are new compared to the recent European Strategy Update [44]:

- The phenomenology of a strong electroweak phase transition is significantly more nuanced than previously envisioned. It can manifest through shifts in the Higgs cubic coupling, but could still occur without any currently or far future measurable deviation in this coupling [45–47]. Deviations in all types of observables are also possibly correlated with the phase transition, including exotic Higgs decays [48].
- Flavored phenomenology is much richer than previously explored. Flavor-violating decays have now richer possibilities and models [49, 50]. Flavor-preserving deviations in consistent light-quark Yukawa couplings now also exist [51, 52], and there are studies for direct probes of this at e^+e^- colliders and related resonance probes from the LHC and other colliders [53].
- Singlet phenomenology, a canonical example in BSM Higgs phenomenology, can be quite a bit more varied, including the introduction of scalar resonances decaying to particles with different masses. These searches were further explored [54–56].
- There are now viable models of triple-Higgs production at the HL-LHC and beyond [52, 55, 57, 58]. The measurement of the quartic coupling should now be considered a standard part of BSM Higgs phenomenology and triple-Higgs and quartic-Higgs measurements should be pursued at future colliders.

We now give a sampling of results based on UV complete models, starting with the simplest extension of the Higgs sector of the SM with an additional scalar singlet S. Despite the simplicity of this type of models, such results display a wide range of phenomenology and connections to fundamental physics questions. For example, with a single degree of freedom from a real scalar, one can connect to the EW phase transition and thereby models of baryogenesis. This Higgs portal can then be connected to dark sectors and DM, or can be viewed as a proxy for models of neutral naturalness. The existence of a new scalar then also applies to the question of whether or not the Higgs is unique and modifies the Higgs potential. This can have implications for the stability of our universe. Thus, the rich phenomenology of the real singlet scalar is quite extensive. One can add additional scalar, i.e. a singlet complex scalar, or even more. The phenomenology can be further complicated and projections onto a two-dimensional plane are not sufficient. In particular, because the masses of the various singlets can be varied, resonance decays have a much wider range of phenomenology. Figure 6-10 illustrates this possibility, where we see that a rate larger than that for SM di-Higgs production (h_1h_1 in Fig. 6-10) is possible [54].

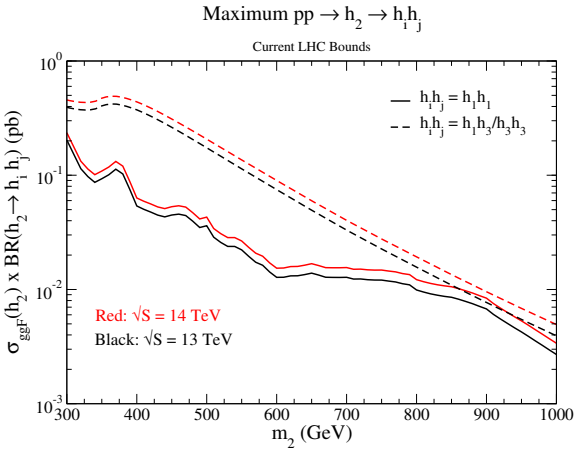


Figure 6-10. *Production of a pair of Higgs bosons in the complex singlet model. In this figure h_1 is the SM Higgs boson, and h_2, h_3 are new scalars with $2m_{h3} < m_{h2}$. The maximum rates allowed by current LHC data are shown in black and projections for $\sqrt{s} = 14$ TeV in red [54].*

Two Higgs Doublet Models (2HDMs) provide the next simplest extension after scalar singlets to the Higgs sector. They are particularly interesting because they allow for a new state with SM gauge charge that can also acquire a vacuum expectation value while naturally allowing for small EW precision corrections. The new doublet allows for additional Higgs bosons beyond the observed 125 GeV CP-even neutral scalar $h(125)$, namely, an additional CP-even neutral scalar H, one CP-odd Higgs boson A, and a pair of charged Higgs bosons $H^{\pm}$. Restricting ourselves to the standard types of 2HDM still allows for an enormous range of phenomenology.

The standard parametrization of the physics is done in terms of a ratio of the vacuum expectation values of the 2HDM states, $\tan\beta$, and a mixing angle $\cos(\beta-\alpha)$ as well as the masses of the various scalar eigenstates.

Precision Higgs measurements probe the model parameter space as demonstrated in Fig. 6-11 [59] and the improvement at lepton colliders for moderate $\tan\beta$ is apparent. Figure 6-11 (right) demonstrates the ability of a high-energy Muon Collider to probe the parameter space of the 2HDM models. We note that the region of moderate $\tan\beta$ is best probed by B decays. Limits from direct searches for the heavier Higgs bosons of the 2HDM are from HL-LHC studies. For high $\tan\beta$, the decay of the heavier Higgs boson to $\tau^+\tau^-$ provides a stringent limit, as seen in Fig. 6-12 [60].

A wider range of phenomenology is allowed in the 2HDMs. In particular 2HDMs do not have to be restricted to the usual four types of natural flavor conserving models. In Fig. 6-13 an example of a Spontaneous Flavor Violation (SFV) 2HDM exemplifies the wide range of phenomenology associated to direct and indirect searches, as well as the new techniques proposed at the ILC for tagging strange quarks directly. These models and measurements can also be further extended into relevant bounds on up and down quark Yukawas as also shown in the ILC white paper [53].

There are of course numerous connections to deeper questions and additional models covered in the Higgs physics Topical Group report [14], but at a general level even Fig. 6-5 does provide important lessons. The first is that many observables map to fundamentally different questions related to the Higgs boson. It is, therefore, non-trivial to connect observables related to Higgs physics with fundamental questions. This has been referred to as the "Higgs Inverse Problem", in analogy with the previously coined LHC inverse problem for BSM physics. Examples of this are given in the Higgs-physics [14] as well as in the EW physics [16] Topical Group reports. The second important lesson, alluded to in Fig. 6-5, is that Higgs related observables

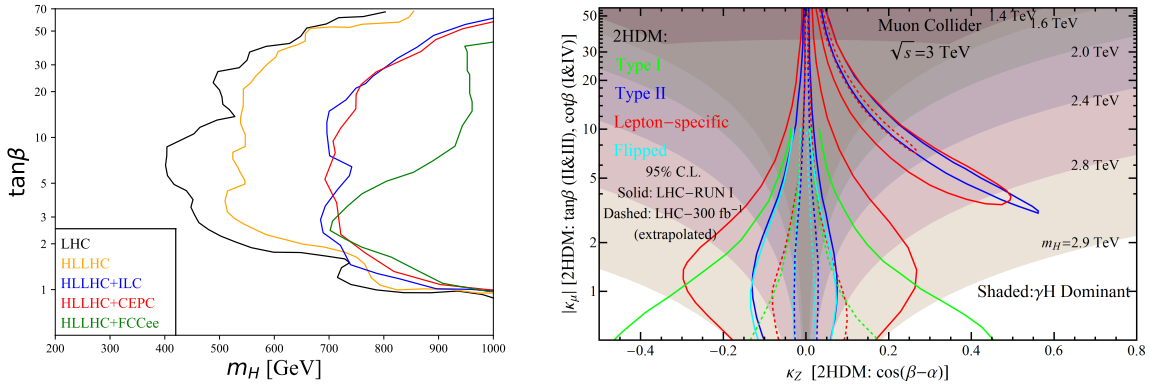


Figure 6-11. *Limits on the parameters of a 2HDM from precision Higgs-coupling measurements. Left: Limits from future e^+e^- colliders combined with limits from the HL-LHC. The allowed region is to the right of the curves. [59]. Right: Limits from a 3 TeV Muon Collider. The TeV scale refers to the mass of the heavier Higgs boson in the 2HDM.*

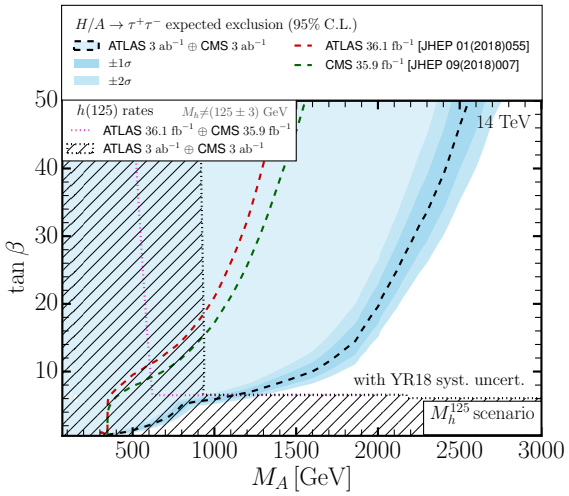


Figure 6-12. *Capability of HL-LHC to probe the scalar sector of the 2HDM.*

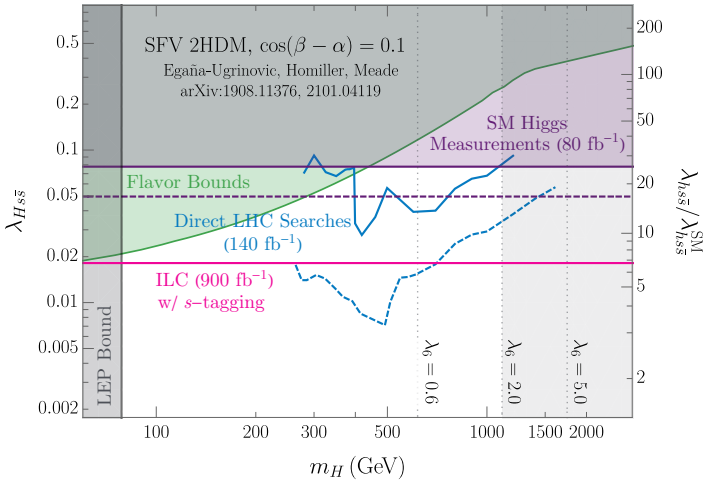


Figure 6-13. *A 2HDM with non standard Yukawa couplings, in the case of an enhanced coupling to the strange quark.*

do not just fall into the standard κ or EFT fits. If there are any deviations in Higgs couplings, or differential measurements etc., there *must* be new physics that couples to the Higgs boson which gives origin to it. How it can be searched for is an ever expanding program and depends on the mass scale of new physics and collider energy. As mentioned earlier in the context of Higgs width measurements, there is an ever expanding program of "Higgs without Higgs" measurements and other types of differential probes being discovered. Suffice it to say, even 10 years after the Higgs discovery, we are still in the earliest stages of fully exploiting the potential connection of the Higgs boson to BSM physics.

6.3.2 Heavy-flavor and top-quark physics

The top quark plays a special role in the EW sector of the SM, with a Yukawa coupling (y_t) of order unity ($y_t = \sqrt{2}m_t/v \approx 1$, where m_t is the top-quark mass and v is the vacuum expectation value of the Higgs field) introducing large quadratic corrections to the Higgs-boson mass, and affecting the stability of the EW vacuum [61]. The top-quark sector is therefore a crucial component of precision EW tests and particularly relevant in searches for BSM physics. Figure 6-14 illustrates the different topics that are addressed through studying top quarks. As the heaviest of all elementary particles, the top quark is relevant for understanding the origin of the Higgs-boson mass and all quark masses. Precise measurements of the masses of the top quark (see Section 6.3.2.1) together with the Higgs boson and the W boson provide a stringent test of the EW sector of the SM. In addition, the top quark decays before it can hadronize, making it the only bare quark that can be studied directly, including at high momenta (see Section 6.4.1). Top-quark production (see Section 6.3.2.2) and decay kinematic information constrain top-quark EW couplings (see Section 6.3.3) and the CKM element V_{tb}. Searches for flavor-changing neutral currents (FCNC) and CP violation focus on the top-quark couplings. Direct searches for new particles and interactions look for top-quark partners, SUSY, and high-mass resonances decaying to top quarks (see Section 6.5). Studies of top-quark production at the highest energies (multi-TeV colliders) probe models of compositeness (see Section 6.5.1). The abundance of top quarks at the LHC makes them ideal for detector calibration of bottom-quark tagging and bottom- and light-quark jet energy calibration. Top-quark production processes constitute an important background in many precision measurements and searches. Lepton colliders operating at or above the top-quark production threshold provide significantly improved measurements of the top-quark mass and its couplings. Precision measurements of top-quark and bottom-quark production at lepton colliders are the inputs needed to significantly improve the sensitivity of third generation and global EFT fits, examples of which are presented in Section 6.3.3. Moreover, running at the Z pole at e^+e^- colliders allows access to high-precision measurements of heavy-quark individual vector and axial-vector couplings. Very precise measurements of the $Z \to b\bar{b}$ rate can be of particular interest for top-quark precision physics given the special relationship of the bottom and top quarks in the SM and BSM models. The prospects for measurements of $Z \to b\bar{b}$ EW precision observables and of EW couplings $g^{bb}_{Z,(L,R)}$ from a SMEFT global analysis at various future colliders are shown in Table 6-8 and Fig. 6-21, respectively.

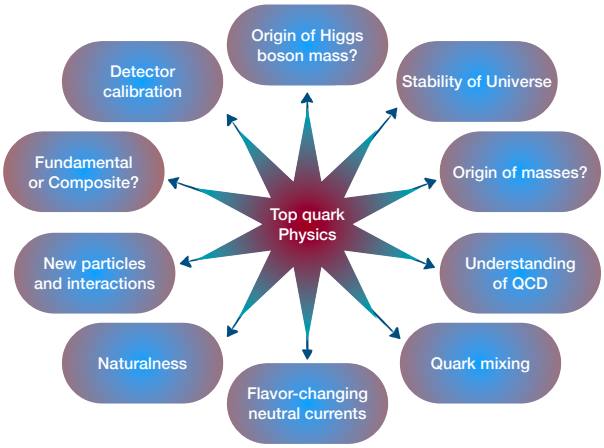


Figure 6-14. *Illustration of the different aspects of the top-quark physics program.*

6.3.2.1 Top-quark mass

The top-quark mass, m_t, is one of the most important parameters of the SM and relevant as an input for precise predictions and for the understanding of SM properties such as the stability of the spontaneously broken vacuum state. Top-quark loop corrections impact the mass of the W boson, e.g. a top-quark mass change of 100 MeV changes the W boson mass by 1 MeV [62]. Thus, given the expected precision on the W mass at the HL-LHC and at future lepton colliders, precisions of better than 500 MeV and 50 MeV are required for top-quark mass measurements at the HL-LHC and at future lepton colliders, respectively, for precision EW fits [63, 64] (see also Section 6.3.3). Since isolated quarks cannot be observed, the top-quark mass is not physical, but a renormalization-scheme-dependent quantity. This scheme dependence can only be well-defined and controlled for mass-sensitive observables that are calculable in perturbation theory (at least at the NLO level). The currently most precise top-quark mass determinations at the LHC are obtained from the direct reconstruction of the top-quark decay products (jets and leptons). Analytic perturbative QCD calculations are not available for the kinematic distribution of these objects, therefore the top-quark mass is extracted from comparisons to predictions by Monte Carlo (MC) event generators (so-called *mass from decay* or *MC mass*). It is estimated that interpreting the mass from decay in a well-defined scheme (like the $\overline{MS}$ scheme) has an uncertainty of about 500 MeV [65, 66]. The current and expected precision for measurements of the mass from decay are compared to the projections from Snowmass 2013 in Fig. 6-15 (left). The recent measurements significantly improved on the projections from 2013.

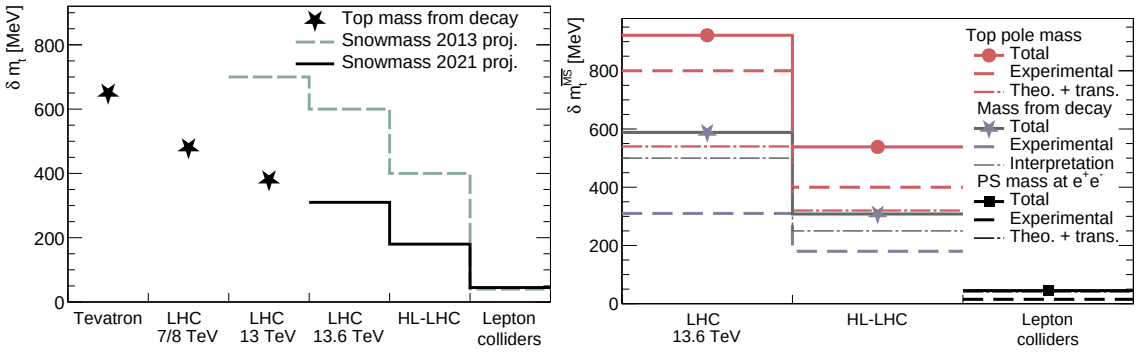


Figure 6-15. *(Left) Comparison of top-quark mass measurements from top decay (MC mass) at the Tevatron and the LHC, and projections for future LHC sensitivity and for future mass sensitivity from a top threshold scan at a lepton collider. The interpretation uncertainty for the mass from decay is not included [15]. (Right) Comparison of projected* $\overline{\text{MS}}$ *top-quark mass determinations from decay and pole-mass measurements at the LHC and HL-LHC and from a PS mass measurement at a future lepton collider. The dashed-dotted lines show the approximate uncertainty in interpreting the mass from decay as* $\overline{\text{MS}}$ *top-quark mass [65, 66] (labeled "Interpretation") or the combined uncertainty from theory and the conversion to the* $\overline{\text{MS}}$ *scheme (labeled "Theo.+trans.").*

Top-quark mass measurements in a well-defined scheme by contrast are based on comparisons of perturbative calculations of differential and total cross sections with measurements that are unfolded to the parton level (so-called *indirect mass* or *pole mass*). Current measurements for a top-quark mass measurement performed in the pole mass scheme have reached a precision of 1.2 GeV [67–69]. The uncertainty is currently dominated by theoretical uncertainties, in particular due to Parton Distribution Functions (PDFs). For the projection, it is assumed here that the theory uncertainty can be reduced through dedicated PDF fits in $t\bar{t}$ events and through higher-order calculations of the $t\bar{t}j$ process.

The ultimate precision in the top-quark mass will be reached in a scan of the top-quark production threshold at a lepton collider (here denoted as *PS mass*). The corresponding expected precision for the PS mass for different e^+e^- collider options is shown in Table 6-5. The overall uncertainty is expected to be limited

by systematic uncertainties, in particular in the theoretical predictions, including the uncertainty on the strong coupling constant α_s. The top-quark width is similarly measured with the highest precision at a lepton collider, in combination with the top-quark mass, in an energy scan of the top-production threshold. The Yukawa coupling of the top quark y_t can be measured in the same scan from the plateau above the top-production threshold [70].

δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}$[fb^{-1}]	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)		40 – 45	
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t HL-LHC		5	
Non-resonant contributions		< 40	
Experimental systematic uncertainty		20 – 30	11 – 20
Total uncertainty		40 – 75	

Table 6-5. *Anticipated statistical and systematic uncertainties in the measurement of the threshold mass, m_t^{PS}, from a threshold scan around 350 GeV obtained with a one-dimensional fit of the top-quark mass, keeping Γ_t, y_t, and α_s fixed. CLIC assumes a lower integrated luminosity than the other facilities. For comparison, the statistical precision achievable with 200 fb^{-1} for CLIC is also given. It should be noted that the results shown for ILC and FCC-ee assume a 8-point scan with a compressed energy range which improves sensitivity for m_t^{PS} at the expense of y_t sensitivity. For the standard 10-point scan assumed for CLIC the statistical uncertainties would be 12 and 10 MeV for ILC and FCC-ee, respectively. The uncertainty due to the current world average for α_s is shown for ILC and CLIC, while for FCC-ee, the run at the Z pole (Tera-Z) will reduce this uncertainty significantly. Concrete studies for CEPC are not yet available, but it can be assumed that uncertainties are similar as for FCC-ee.*

To be able to compare the projections for the different top-quark mass measurements, they have been converted to projections for the $\overline{MS}$ top-quark mass, shown in Fig. 6-15 (right). The dash-dotted lines show the approximate uncertainty in interpreting the mass from decay as a $\overline{MS}$ top-quark mass [65, 66] or the combined uncertainty from theory and the conversion to the $\overline{MS}$ scheme (known to $\mathcal{O}(\alpha_s^4)$ in QCD) in case of the pole and PS mass measurements.

6.3.2.2 Top-quark production processes

Top quarks are produced copiously at hadron colliders in many different production modes, $t\bar{t}$, single top, and both modes in association with other quarks and bosons. Modeling the different processes requires precision higher-order QCD calculations with heavy quarks. The cross sections for the production of top-quark pairs [71], as well as top-quark pairs in association with various other particles are shown in Fig. 6-16 [15]. Measuring all of these processes is possible with high precision at the HL-LHC. Even the process with the lowest production cross section, the production of four top quarks, can be measured with an uncertainty of about 20% at the HL-LHC, and should be measurable to a few percent at higher-energy hadron colliders (including FCC-hh) [72, 73]. This production mode has the highest energy threshold of all top-quark-related SM processes studied at hadron colliders. It is sensitive to y_t and BSM interactions, for example contact interactions [72]. The measurements of $t\bar{t}H$ production directly probe the top Yukawa coupling. The measurements of $t\bar{t}Z$, $t\bar{t}\gamma$ have intrinsic value, as they form the first constraints on the EW couplings of the top quark. Precision measurements of the processes shown in Fig. 6-16 and the corresponding single

top-quark processes are utilized in global EFT fits. It should be possible to reach a precision of O(1%) for $t\bar{t}$ production, larger for other processes. This requires careful calibration, improved modeling of top-quark and other processes, and improved theory calculations; currently the scale uncertainty on $\sigma(t\bar{t})$ is about 3% at NNLO QCD with NNLL soft-gluon resummation [74], while the PDF uncertainty is about 3% [75]. Extending the differential top-quark measurements to high, multi-TeV transverse momenta gives sensitivity to 4-fermion interactions involving the third generation.

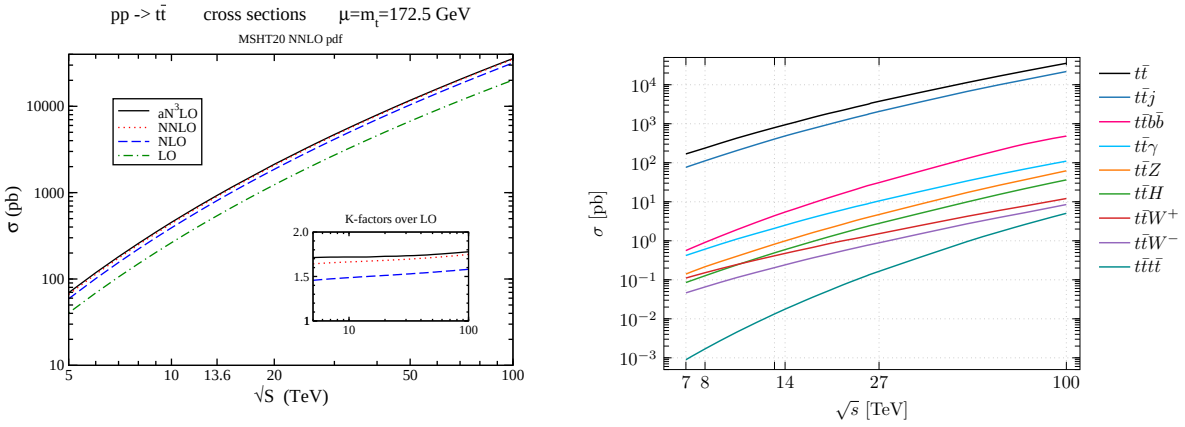


Figure 6-16. *Total cross sections as a function of the center-of-mass energy $\sqrt{s}$ at pp colliders for (left) $t\bar{t}$ production at LO, NLO, N^2LO and approximate N^3LO [71] and for (right) various $pp \to t\bar{t}X$ processes at NLO. The $pp \to t\bar{t}$ cross section is also shown for reference. Light objects are also required to have $p_T > 25$ GeV and $|\eta| < 2.5$, while jets are clustered using the anti-k_T algorithm with $R = 0.4$.*

At lepton colliders running at or above the top-quark production threshold allows for high-precision measurements of $t\bar{t}$ production and of the couplings of the top-quark to the Z boson. These measurements, as well as the corresponding measurements of the production of bottom-quark pairs at similar precision, will allow to significantly extend the sensitivity of global EFT fits, see Fig. 6-17. Producing $t\bar{t}$ in association with the Higgs, W or Z bosons requires significantly higher center-of-mass energies at a lepton collider.

6.3.2.3 Top-quark coupling measurements and EFT fits

The measurements of cross sections of top-quark production processes provide important inputs to global EFT fits [76]. Differential production measurements and studies of top-quark decay and top-quark final state correlations provide further constraints [77]. At hadron colliders, these include top-quark pair and single top-quark production processes, and associated production, measured differentially. The precision of the measurements is limited by systematic uncertainties, the largest of which are due to jet energy calibration and QCD modeling of the top-quark final states. At lepton colliders, the final state can be fully reconstructed, and most measurements are effectively background-free, in contrast to hadron colliders. The lepton collider measurements constrain all EW couplings of the top quark. The gain in precision is particularly pronounced in the couplings to neutral bosons that are tested directly in $e^+e^- \to t\bar{t}$ production. The coupling to the W boson is constrained strongly already in helicity fraction measurements at the Tevatron and the LHC and the improvement compared to HL-LHC is not as dramatic (see Section 6.3.3). Figure 6-17 shows the reach of the HL-LHC and the improvement that can be expected from adding lepton collider data to a global EFT fit of the Wilson coefficients relevant for top-quark couplings. The fit uses cross sections for various top-quark

production processes (Section 6.3.2.2) and angular correlations at the HL-LHC, and optimal variables at the lepton collider.

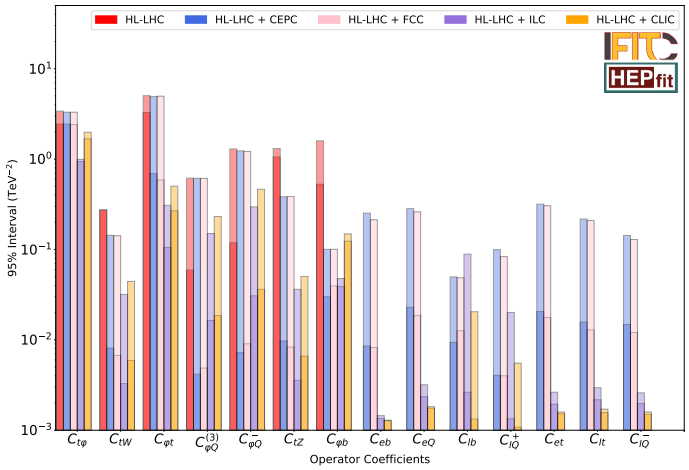


Figure 6-17. *Comparison of the constraints expected from a combination of HL-LHC and lepton collider data on Wilson coefficients for EFT operators relevant to top-quark couplings, see Section 6.3.3. The solid bars provide the individual limits of the single-parameter fit and the shaded ones the marginalised limits of the global fit. The details of the fit can be found in Refs. [78, 79].*

6.3.2.4 BSM physics from top-quark physics

Besides indirect searches for BSM physics in the EFT framework, the top quark is also a sensitive probe in direct searches for new physics. BSM models which aim to protect the Higgs boson mass from large quadratic corrections beyond the EW energy scale are often closely connected to the top quark, such as low-energy SUSY. For example, in [80] the correlation of the spins of the two top quarks in $t\bar{t}$ production at the LHC are used to constrain SUSY models with top squarks with masses close to the top-quark mass (and small neutralino mass). Figure 6-18 shows the projected limit for a 30 GeV-wide "corridor" in stop mass ($m(\tilde{t})$) and neutralino mass ($m(\chi_0)$) around the top-quark mass ($m(\tilde{t}) - m(\chi_0) - m(t)| < 30$ GeV) [80]. The width of the corridor corresponds to the experimental resolution and the region where direct stop searches are not sensitive because of the large $t\bar{t}$ background. The limits expected for the HL-LHC are a factor two (at low $m(\tilde{t})$) to ten (at high $m(\tilde{t})$) better than the Run 2 limits in this region. The predicted SUSY stop pair production cross section in this region is between 10 pb and 100 pb, meaning the entire area will be excluded.

As the heaviest fermion, it is also expected to play a central role in models of compositeness, together with the Higgs boson [81]. Examples of the phenomenology of these type of models in the top-quark sector are the occurrence of new fermionic resonances (top partners), anomalous 4-top quark production, and modified top Yukawa and top-EW couplings. For example, Fig. 6-19 compares the reach of future colliders in the plane of mass scale and coupling $g*$ for a model of total right-handed top-quark compositeness, giving rise to sizeable 4-top Wilson coefficients [82].

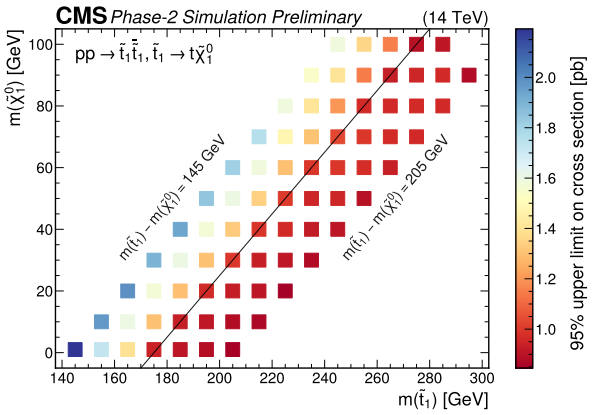


Figure 6-18. *Limit on the cross section for SUSY stop production in the compressed region where the stop mass ($m(\tilde{t})$) is close to the neutralino mass ($m(\chi_0)$), $m(\tilde{t}) - m(\chi_0) = 175$ GeV [80]. Every point in this plot is excluded [80].*

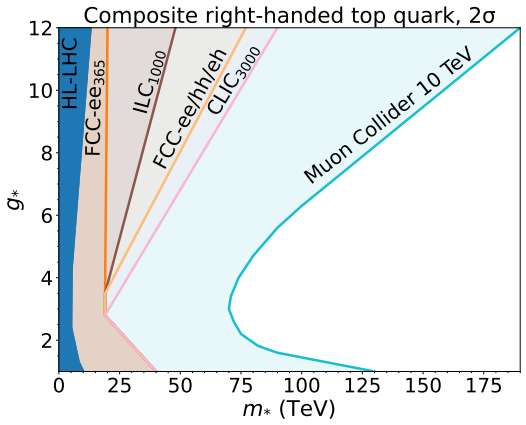


Figure 6-19. *Exclusion (2-σ) sensitivity projections for compositeness models at future colliders as labeled, for models where both the Higgs boson and the top quark with right-handed couplings are composite. Plot based on Refs. [81, 82].*

Top-quark interactions are also an excellent probe of FCNC involving the third generation of leptons. Searches for FCNC interactions in single top-quark production at hadron colliders (sensitive to gluon FCNC interactions) and lepton colliders (sensitive to photon and Z boson FCNC interactions) take advantage of needing lower center-of-mass energy to produce one top quark rather than two. The large samples of top quarks collected at the LHC and expected at the HL-LHC allow for searches in the top-quark decay (sensitive to photon, Z boson, and Higgs FCNC interactions). The limits on the top decay branching ratios are around 10^{-4} with the Run 2 dataset, these will be improved to around 10^{-5} at the HL-LHC. Lepton colliders are sensitive to FCNC couplings of the top quark to the photon and the Z boson, especially at energies below the $t\bar{t}$ production threshold [70, 83]. The production of a single top quark together with an up or charm quark provides a unique final state signature. Combining runs at multiple center-of-mass energies provides additional sensitivity, especially at the highest energies reached in e^+e^- only by CLIC [84]. This is an area where a Muon Collider might also provide additional sensitivity.

6.3.2.5 Heavy-flavor and top-quark physics summary

Table 6-6 compares a few top-quark measurements between different future collider options. Each of the measurements can be improved at future colliders beyond the precision at the HL-LHC. Significantly improving the precision of the top-quark Yukawa coupling beyond the 2-4% uncertainty expected at the HL-LHC [30] and measuring the top-Higgs coupling in $t\bar{t}H$ events requires a high-energy lepton collider at a center-of-mass energy of at least 500 GeV or a hadron collider. The projected top-quark mass uncertainty at lepton colliders is obtained from Table 6-5, taking the lower end of each uncertainty range. The precision of the coupling measurements to the SM bosons will all be significantly improved at a lepton collider operating at or above the top-production threshold. The four-top coupling can be probed at hadron colliders, or at lepton colliders running at sufficiently high energies. Searches for FCNC via the Z boson or photon are done in top-quark decays at hadron colliders, the sensitivity is significantly extended at lepton colliders operating as a Higgs factory. These projections also rely on a significant theoretical effort to meet the tremendous challenges in providing theory predictions at the required level of precision.

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024

Table 6-6. *Anticipated precision of top-quark Yukawa coupling and mass measurements, and of example EFT Wilson coefficient for the top-quark coupling to W, Z and Higgs bosons, as well as a four-top Wilson coefficient. The reaches of the CEPC and SPPC are expected to mirror those of the FCC-ee and the FCC-hh respectively.*

6.3.3 Electroweak precision physics and new physics constraints

The precise measurement of physics observables and the test of their consistency within the SM are an invaluable approach, complemented by direct searches for new particles, to determine the existence of physics beyond the SM.

Indirect searches for new physics, which exploit off-shell and loop contributions of new particles, allow one to explore a much wider range of energy scales than those probed by direct searches in specific BSM scenarios. Such indirect BSM effects are typically inversely proportional to some power of the mass scale of the new degrees of freedom, so that high precision is crucial for probing large energy scales. The achievable precision of an experiment is determined by the statistics of the collected data sample, the experimental and theoretical systematic uncertainties, and their correlations.

Electroweak precision physics

The current precision for a few selected electroweak precision pseudo-observables (EWPOs) is listed in Table 6-7. The HL-LHC with integrated luminosity of 3000 fb^{-1} can make improved measurements of certain EWPOs. The effective weak mixing angle can be extracted from measurements of the forward-backward asymmetry in Drell-Yan production, $pp \to \ell^+\ell^-$ ($\ell = e, \mu$), while the W-boson mass can be determined from measurements of $pp \to \ell\nu$. Both measurements crucially depend on precise knowledge of PDFs and theory input for QCD and EW corrections, where the SM has to be assumed for the latter.

Future high-luminosity e^+e^- colliders can be used to study the masses and interactions of electroweak bosons to much higher precision than before. We here focus on four collider proposals: ILC [33,87,88], CLIC [89,90], FCC-ee [36, 91], and CEPC [92, 93]. For ILC, CLIC and FCC-ee, we use the run scenarios and integrated luminosities in Table 6-1, whereas for CEPC the 50 MW upgrade is assumed, which corresponds to 100 ab^{-1} on the Z pole, 6 ab^{-1} at the WW threshold, and 1 ab^{-1} at the $t\bar{t}$ threshold [93]. For ILC also the Giga-Z option with 100 fb^{-1} on the Z pole is considered. [Note that a Z-pole run is also proposed as a possible option for CLIC [94].] Table 6-8 summarizes the achievable precision for a range of EWPOs.

EWPO Uncertainties	Current	HL-LHC
Δm_W (MeV)	12 / 9.4†	5
Δm_t (GeV)	0.6*	0.2
$\Delta \sin\theta^{\ell}_{\rm eff}$ ($\times 10^5$)	13	< 10

† The recent W mass measurement from CDF with 9.4 MeV precision [85] has not yet been included in the global average [86].

* This value includes an additional uncertainty due to ambiguities in the top mass definition (see [15] for more details).

Table 6-7. *The current precision of a few selected EWPOs, based on data from LEP, SLC, Tevatron and LHC [86], and expected improvements from the HL-LHC [30]. Δ (δ) stands for the absolute (relative) uncertainty.*

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\rm had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

Table 6-8. *EWPOs at future e^+e^- colliders: statistical error (estimated experimental systematic error). Δ (δ) stands for absolute (relative) uncertainty, while * indicates inputs taken from current data [86]. See Refs. [33, 42, 93, 95–97].*

The table separately lists the expected statistical and experimental systematic uncertainties. Note that the latter are based on assumptions about future performance improvements that cannot be substantiated at this time. Uncertainties due to the physics modeling affect all collider proposals equally. As part of the Snowmass 2021 process, a consistent set of assumptions is being used and applied uniformly. See EF04 Topical Group report for more details [16].

The impact of these estimated future precision measurements on the indirect determination of the Higgs-boson and top-quark mass is illustrated in Fig. 6-20. The dependence on m_H and m_t appears in loop

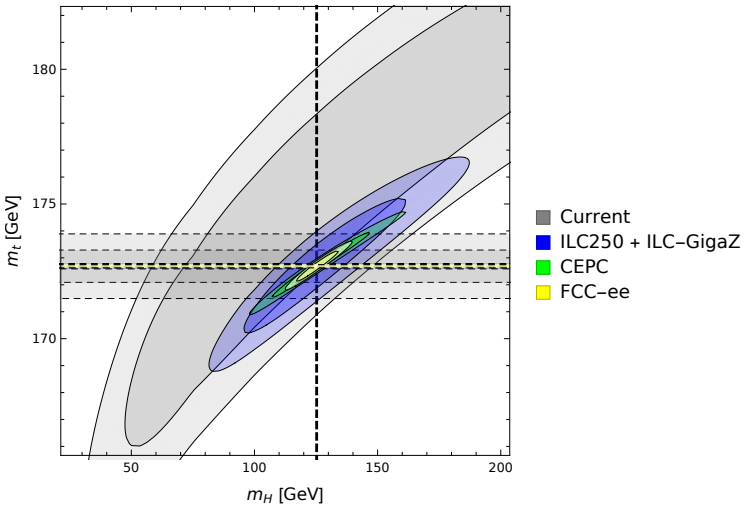


Figure 6-20. *Indirect sensitivity to m_H and m_t for a fit of SM theory predictions to current and projected future data for electroweak precision tests (W mass and Z-pole quantities). For comparison, the direct measurement precision is also shown (on the scale of the plot the width of the m_H band is not visible). The light (dark) shaded areas depict 95% (68%) confidence level regions. For the future collider scenarios it is assumed that the central values coincide with the SM expectations.*

corrections to the SM theory predictions for Z coupling parameters and the W mass, and their agreement with direct measurements of these masses is a highly non-trivial test of the SM.

For "canonical" electroweak precision measurements (Z-pole, WW threshold), circular e^+e^- colliders (FCC-ee, CEPC) have in general a higher sensitivity than linear colliders (ILC, CLIC) due to the high luminosity at center-of-mass energies below 200 GeV. Beam polarization at the linear colliders improves their sensitivity and can help to control systematics. In particular, for a linear collider run on the Z pole, beam polarization would enable measurements of the asymmetry parameters A_f with a precision that is only a factor of a few worse than for circular colliders, in spite of several orders of magnitude larger statistics for Z-pole physics at circular colliders.

For many of the most precisely measurable precision observables at linear colliders, the most significant source of experimental systematics stems from the polarization calibration. For the circular colliders, on the other hand, modeling uncertainties for hadronic final states appear to be the dominant systematic error source.

To exploit the full potential of the anticipated precision of any future e^+e^- collider, theory inputs are needed on multiple fronts. Accurate MC tools for the simulation of QED and QCD radiation are crucial for the evaluation of acceptance effects, and theory calculations including higher-order effects are needed for the prediction of irreducible backgrounds. For the interpretation of electroweak precision measurements, one needs to compare the measured values to their expectation within the SM, which requires multi-loop theory computations. For the anticipated experimental precision FCC-ee, CEPC, ILC or CLIC, the current state of the art of theory calculations needs to be extended by at least one order of perturbation theory, i.e. N^{-2}LO/NLL contributions for MC tools and backgrounds, and N^{3}LO and partial N^{4}LO contributions for the SM predictions. See EF04 Topical Group report for more details [16].

The SM predictions also rely on other SM parameters as inputs, such as the electromagnetic coupling at the weak scale, $\alpha(m_Z)$, the top-quark mass, m_t, and the strong coupling, α_s. The current uncertainties for these

EWPO uncertainties	Current param. error	Projected param. error	
		Scenario 1	Scenario 2
Δm_W (MeV)	5	2.8	0.6
$\Delta\Gamma_Z$ (MeV)	0.5	0.3	0.1
$\Delta \sin^2\theta^\ell_{\text{eff}}$ ($\times 10^5$)	4.2	3.7	1.1
ΔA_ℓ ($\times 10^5$)	30	25	7.5
δR_ℓ ($\times 10^3$)	6	3.2	1.3

Input par. uncertainties	Δm_t [GeV]	Δm_H [GeV]	Δm_Z [MeV]	$\Delta(\Delta\alpha)$	$\Delta\alpha_s$
Current	0.6	0.17	2.1	10^{-4}	9×10^{-4}
Scenario 1	0.3	0.02	0.8	10^{-4}	5×10^{-4}
Scenario 2	0.05	0.01	0.1	3×10^{-5}	2×10^{-4}

Table 6-9. *Impact of uncertainties of SM input parameters on the prediction of a few selected EWPOs in top table (see Ref. [98]). Current uncertainties are compared to two future scenarios in the bottom table.*

parameters would severely limit the possibility for future high-precision studies, and thus it is necessary to perform improved measurements of these quantities at the future e^+e^- colliders. See sections 6.3.2.1 and 6.4.1 for more information.

The impact of the uncertainties of the SM input parameters on the interpretation of electroweak precision measurements is illustrated in Table 6-9. In addition to the current measurement precision, two future scenarios are considered, where Scenario 1 assumes improvements from a Higgs factory with moderate luminosity spent on the Z pole and no $t\bar{t}$ running, whereas Scenario 2 displays the full potential of achievable precision at future e^+e^- colliders. Note that the dependence of the predictions for Γ_Z and R_ℓ on α_s are to a certain extent circular, since these quantities would be used for the extraction of the strong coupling constant at future e^+e^- colliders [99].

Experiments at lower-energy e^+e^- colliders, lepton-proton colliders, or neutrino scattering facilities can deliver complementary information about electroweak quantities. For instance, a beam polarization upgrade of SuperKEKB/Belle II can enable a measurement of the electroweak mixing angle via tests of vector coupling universality in neutral currents with unprecedented precision. Electron-proton colliders such as EIC, LHeC and FCC-eh could provide information about the running electroweak mixing angle at scales of a few tens of GeV and enable the separate determination of up- and down-quark electroweak couplings with high precision.

A Muon Collider with center-of-mass energy $\sqrt{s} \approx 91$ GeV [100] would also be very interesting for electroweak precision measurements, but more studies are needed.

6.3.4 EFT and new physics

6.3.4.1 Multi-boson processes

The SM predicts the existence of multi-boson interactions, which give rise to final states with two or three bosons. Anomalies in the rate and kinematics of these final states can be indicative of new physics not currently described in the SM. Such anomalies can be parametrized through modifications of the strength

or form of the SM multi-boson vertices. A newer approach consists in using EFT operators of dimension six or above, where measurements of multi-boson processes can be recast as determinations of the Wilson coefficients of these operators.

It shall be noted that the sensitivity to BSM effects, or, in other terms, the upper limits to the Wilson coefficients of new operators, scale with a power of the center-of-mass energy, thus making multi-TeV colliders the ideal tools for studying these final states. At this time, the most promising avenues for reaching multi-TeV energies are proton-proton colliders or $\mu^+\mu^-$ colliders.

High-energy ($>$ 1 TeV) lepton colliders are effectively boson colliders. The total cross section for many production processes is dominated by vector-boson fusion (VBF) and/or vector-boson scattering (VBS) contributions. However, for studies of BSM effects at very high invariant masses, non-VBF processes become typically more dominant.

At multi-TeV lepton colliders, multiple electroweak gauge-boson production is ubiquitous, and new theoretical tools are needed for calculating and simulating these effects (e.g. theory modeling of EW PDF and fragmentation, initial-state - ISR - and final-state - FSR- radiation).

Plentiful experimental results with multi-boson final states are available. Both the ATLAS and CMS collaborations have measured di-boson [101–109], tri-boson processes [110–113], as well as VBF/VBS processes [114–124], which are characterized by a $VVjj$ final state. Di-boson final states include W^+W^-, same-sign $W^\pm W^\pm$, WZ, ZZ, $Z\gamma$. Tri-boson final states include $W\gamma\gamma$, $Z\gamma\gamma$, $WV\gamma$ (where $V = W, Z$), and WVV' (where $V, V' = W, Z$).

Bounds on new physics have been determined in the language of anomalous gauge-boson couplings (aGCs) [101, 104–106, 109] and effective operators [102, 106–108, 113, 120–123]. The latter is theoretically preferred since it provides a consistent power counting and allows one to implement theoretical consistency constraints. In these studies, only one or two aGCs/operators are allowed to be non-zero at the same time, i.e. no full aGC/SMEFT analysis has been performed.

The most up-to-date limits on gauge-coupling anomalies are available at Refs. [125, 126]. Expected limits at the end of the HL-LHC and potential HE-LHC runs are reported in Ref. [127].

There are ongoing studies for the determination of aGCs or multi-gauge boson SMEFT operators at future hadron and lepton colliders (see e.g. Ref. [128, 129]). Preliminary results indicate that a 100-TeV pp collider or a multi-TeV $\mu^+\mu^-$ collider would have strongly enhanced sensitivity to these BSM effects compared to the LHC, but more work is needed to obtain a comprehensive picture.

6.3.4.2 SMEFT global fits

Assuming new physics scales are significantly higher than the EW scale, EFTs provide a model-independent prescription that allows us to put generic constraints on new physics and to study and combine large sets of experimental data in a systematically improvable QFT approach. All new physics effects are represented by a set of higher dimensional operators which consist of only the SM fields and respect the SM gauge symmetries.

The EFT approach has some features that are of particular interest for studying precision EW physics, for instance: it provides a well-defined theoretical framework that enables the inclusion of radiative corrections for both the SM and BSM parts; and the synergies between different precision EW measurements can be explored globally so that a comprehensive picture of the constraints on new physics can be drawn. However, the EFT approach also has some practical limitations since it has in principle an infinite number of degrees

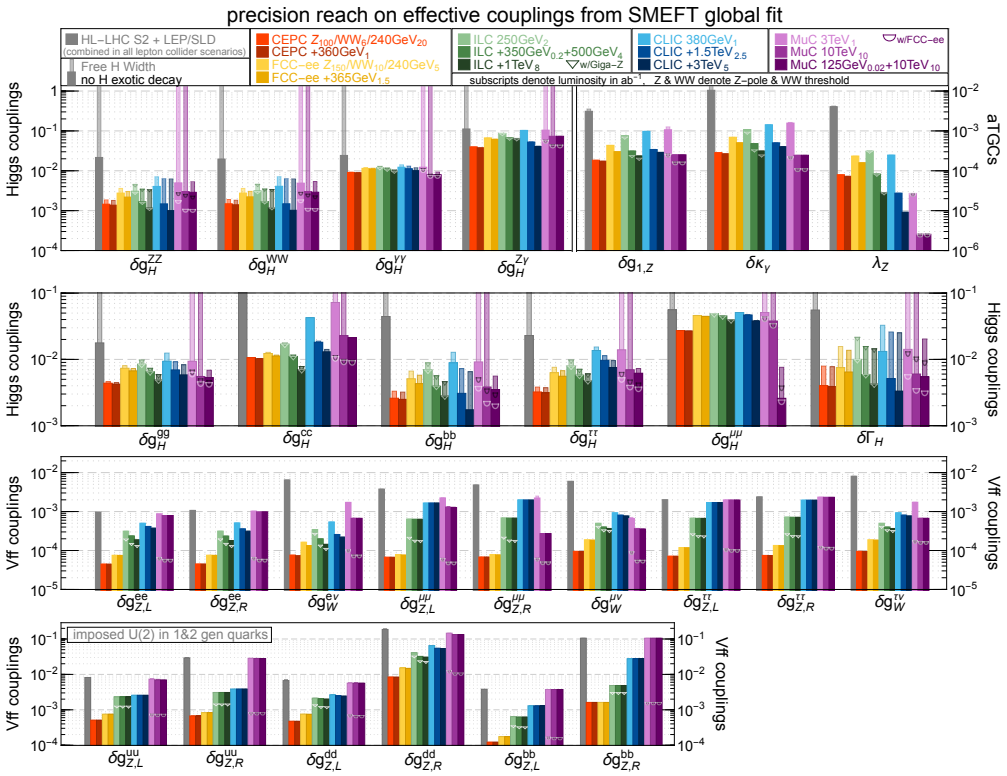


Figure 6-21. *Precision reach on Higgs and electroweak effective couplings from an SMEFT global analysis of the Higgs and EW measurements at various future colliders. The wide (narrow) bars correspond to the results from the constrained-Γ_H (free-Γ_H) fit. The HL-LHC and LEP/SLD measurements are combined with all future lepton collider scenarios. For e^+e^- colliders, the high-energy runs are always combined with the low energy ones. For the ILC, the (upper edge of the) triangle mark shows the results for which a Giga-Z run is also included. For the Muon Collider, three separate scenarios are considered. The subscripts in the collider scenarios denote the corresponding integrated luminosity of the run in* ab^{-1}.

of freedom, and it is only an adequate description if the new physics scales are larger than the experimentally reachable energies. In a realistic global EFT fit, various flavor assumptions and truncations to the lowest order of relevant operators often have to be applied.

A model-independent parametrization of the new-physics reach of different colliders is given by the SMEFT framework, where the SM is extended by higher-dimensional operators, with the leading contribution to most observables furnished by dimension-6 operators. Several subsets of such dimension-6 operators have been investigated in a series of global fits across a large number of observables: (a) operators contributing to electroweak gauge-boson interactions; (b) operators contributing to Higgs interactions; (c) operators contrbuting to top-quark interactions; and (d) operators contributing to four-fermion contact interactions.

For Snowmass 2021, the global EFT fit for the European Study Group (ESG) [42] has been extended in a few directions [78]: the consistent implementation of full EFT treatment in $e^+e^- \to W^+W^-$ using optimal observables; the new inclusion of a large set of 4-fermion operators; a more complete set of operators that are related to top-quarks. In all the fits, operators for third-generation fermions are treated independently, without assuming flavor universality, and in some cases even universality between the first two generations has been lifted. However, no flavor-changing operators were included in the analysis. The projections of the

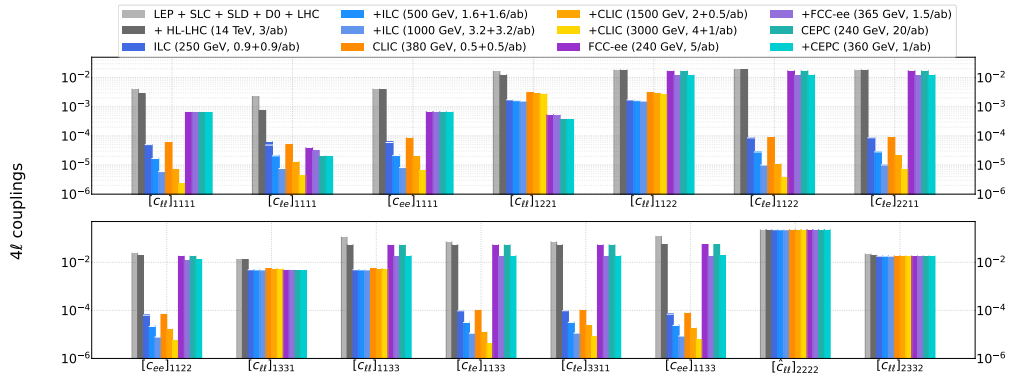


Figure 6-22. *Precision reach on a subset of 4-fermion operators from a SMEFT global fit at various future lepton colliders. "LEP+SLC+SLD" represents current measurements which are always combined in the future collider scenarios. The horizontal white line for ILC illustrates the global fit results when the pole observables from its Giga-Z option are included.*

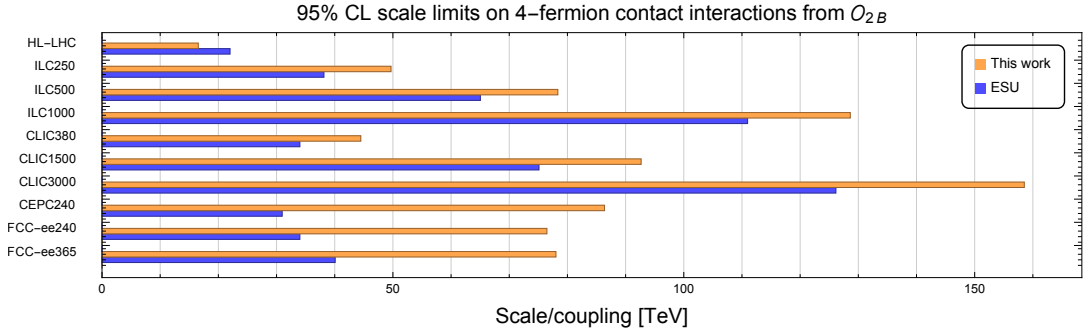


Figure 6-23. *95% CL exclusion reach of different colliders on four-fermion contact interactions from the operator O_{2B} (numbers for ESG are taken from Ref. [130]).*

uncertainties of required input observables are provided by EF01 for Higgs related observables [14], EF03 for top-quark related observables [15], EF04 for W/Z related observables [16], and the Rare Process and Precision Measurements Frontier for a set of low-energy measurements [9]. Care has been taken to ensure that the various inputs are consistent and based on similar assumptions, e.g. by using extrapolations to compare inputs from two different e^+e^- colliders.

Figure 6-21 displays the result of the global EFT fit for the subset of operators that affect Higgs and EW observables. Instead of showing the projected constraints on the Wilson coefficients of the operators considered, they have been translated into constraints on the effective Higgs and gauge-boson couplings. See EF04 Topical Group report for more details [16].

Generally, future lepton colliders have the best reach for many of the aforementioned operators. Circular e^+e^- colliders have the highest sensitivity to EW operators, due to the large statistical precision of Z-pole and WW-threshold measurements. All lepton colliders (e^+e^- and $\mu^+\mu^-$) are comparable in their reach for Higgs operators, although a multi-TeV Muon Collider cannot constrain exotic Higgs decays in a model-independent way, and the combination with a run on the s-channel Higgs resonance would be required for this purpose. Since some of the same operators contribute to Z-pole precision observables, as well as to HZ, WW, and ZZ pair production cross sections, the operator constraints extracted from the latter can

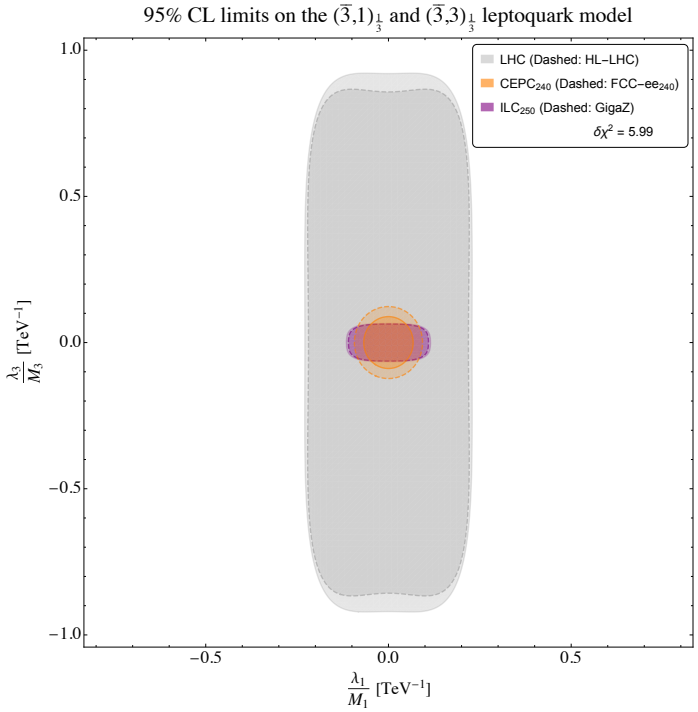


Figure 6-24. *95% CL exclusion reach of different colliders on the leptoquark model parameters. Only future e^+e^- scenarios with energies below the $t\bar{t}$ threshold have been considered since the analysis did not include any top-quark observables.*

be improved by performing a combined fit with Z-pole data. This effect is more significant for circular e^+e^- colliders than for linear e^+e^- colliders, since for the latter beam polarization helps to disentangle the contributions of different operators in $HZ/WW/ZZ$ pair production processes.

Figure 6-22 shows a selection of results for a fit that combines a set of Higgs and EW operators with 4-fermion operators. The latter are better constrained at linear e^+e^- than circular e^+e^- machines, taking advantage of the higher energy reach and beam polarizations[2]. A recent analysis of the sensitivity of Muon Colliders to new 4-fermion interactions can be found in Ref. [81]. Low-energy measurements (from fixed-target neutrino and electron scattering, tau and meson decays) are needed to close the fit for four-fermion operators. For complete results of the combined fit with 4-fermion operators, see Ref. [16].

Not only four-fermion operators, but also top-quark electroweak operators are best constrained at lepton colliders with $\sqrt{s} \geq 500$ GeV, and measurements at two or more values of $\sqrt{s}$ are crucial for breaking degeneracies. Many constraints on top-quark operators are improved by combining e^+e^- and (HL-)LHC inputs and exploiting synergies between them. See EF04 Topical Group report for more information [16].

The results from global fits can be also interpreted in terms of constraints on simple BSM benchmark models. Figure 6-23 is one example for a scenario where a flavor-universal 4-fermion contact interaction is introduced, which can be described by the single operator O_{2B} [131]. A second example is shown in Fig. 6-24, which extends the SM by two leptoquark fields, an SU(2) singlet with Yukawa coupling λ_1 and mass M_1, and an SU(2) triplet with Yukawa coupling λ_3 and mass M_3 [132, 133]. This model generates several 4-fermion interactions, and the bounds on the latter can be translated to bounds on the model parameters shown in

[2]For now the global fit for 4-fermion operators did not include Muon Colliders.

the figure, where the constraining power of future e^+e^- colliders is manifest. More examples on composite Higgs models and Z' models are also discussed in the BSM Topical Group report [18].

6.4 QCD and Strong Interactions

The fundamental theory of strong interactions, QCD, plays a unique role in the Standard Model. Being a confining gauge theory, it is an interesting quantum field theory to study in its own right. It is also a crucial tool to enable discovery at every high-energy collider. It predicts a rich panoply of phenomena associated with both perturbative and non-perturbative dynamics of the strong interactions. Continued success of the high-energy and nuclear physics research program hinges on an improved understanding of both regimes, as well as the dynamical transition between them.

Future SM measurements and new physics searches will allow the exploration of new kinematic regions, such as very high transverse momentum and very forward rapidities, where large scale hierarchies may induce hitherto unseen QCD effects. The upcoming era — featuring the HL-LHC, Belle II, the EIC, new advances in theory including lattice QCD, and potentially a Higgs factory — will be a new golden age for QCD, easily rivaling the 1990's when the Tevatron, HERA, and LEP were all operating.

Measurements of jet, heavy-quark, and top-quark cross sections at the HL-LHC will test perturbation theory to an unprecedented level, and constrain PDFs [134] as well as the strong coupling α_s [99]. Accurate prediction of QCD radiative effects will remain a key factor in precision measurements of the W-boson and top-quark masses, and of the weak mixing angle at hadron colliders, as discussed in Sec. 6.3.3. Versatile techniques are refined at the LHC to analyze the internal particle composition of hadronic jets [135, 136]. These techniques are widely employed to minimize the impact of pileup, probe fundamental and emergent properties of the strong force, enhance precision of measurements of highly-Lorentz-boosted particles, and extend the sensitivity of searches for new particles (cf. Sec. 6.4.1) [137].

Detection of the decay products of far-forward hadrons at the proposed Forward Physics Facility (FPF) at the HL-LHC (Sec. 6.4.3) would enable QCD studies and BSM searches in a novel high-energy regime [138, 139]. The FPF would observe neutrinos of all flavors, and possibly new particles, on its own or in coincidence with ATLAS, leading to deeper understanding of small-x dynamics, forward heavy-flavor production, neutrino scattering in the TeV range, and the structure of nuclear matter.

Due to their QCD-neutral initial state, e^+e^- colliders offer the cleanest environment to study QCD dynamics. Belle II will perform various measurements at low and medium energies [140], such as the cross section for $e^+e^- \to$ hadrons (in particular two pions), from which the leading-order hadronic contribution to the anomalous magnetic moment of the muon can be extracted. Unprecedented statistical precision combined with low backgrounds will enable highly impactful studies of factorization, QCD evolution, and multidimensional correlation functions, which will help to constrain MC models of hadronization for the HL-LHC program. There has been much progress since LEP in understanding hadronic final states at e^+e^- colliders, driven by techniques to analyze jet substructure and energy correlation functions. Measurements of event shapes will enable precision extractions of α_s [141, 142]. These colliders offer a particular advantage of producing pure samples of gluon jets via the process $e^+e^- \to hZ$, with Z decaying to leptons, and the Higgs boson decaying to gg [143]. Better understanding of b-quark showering and hadronization, as well as b-quark production by secondary gluons, will be important: these are leading sources of systematic uncertainty in the measurement of the b-fraction in hadronic decays (R_b) and the b forward-backward asymmetry in Z decays [144].

Proposed Muon Colliders offer a physics reach for discoveries that is similar to that of proposed high-energy hadron colliders. While operating at few-TeV energies, the Muon Colliders maintain appealing

experimental aspects of lepton collider environments, e.g. a lack of pileup and underlying event. Advanced pileup mitigation techniques studied at the LHC could provide versatile handles to remove beam-induced background contamination during reconstruction [145–148].

The EIC physics program [149], dedicated to exploration of hadronic matter, has strong synergies with the HL-LHC and FPF. The EIC can precisely measure the hadronic structure in deep inelastic scattering (DIS) through both neutral- and charged-current reactions, to perform spin-dependent three-dimensional tomography of nucleons and various ion species using highly-polarized beams for electrons and light ions. With its variable center-of-mass energy and excellent detection of final hadronic states, the EIC can resolve the flavor composition of unpolarized proton PDFs in the kinematic region of relevance for BSM searches at the HL-LHC, but at QCD scales of only a few (tens of) GeV. The EIC program will stimulate the development of theoretical and numerical tools for QCD at the interface between particle and nuclear physics.

Proposed lepton-hadron colliders operating in the TeV energy range (Muon-Ion Collider [150], LHeC [151, 152], FCC-eh [153]) would be both machines for subpercent-level measurements of α_s, nucleon structure, EW and Higgs couplings, as well as discovery machines to search for new physics such as compositeness and leptoquarks. Future hadron-hadron colliders, including the FCC-hh [41] operating at 100 TeV, would open unprecedented opportunities for precision measurements in perturbative and non-perturbative QCD. Their physics program would require innovative developments both in particle detection and QCD theory (Sec. 6.4.5), such as parton distributions for electroweak bosons, predictions for boosted final states inside jets, and new types of event generators.

6.4.1 Perturbative QCD

Precision calculations. Perturbative precision calculations are crucial for measurements of SM parameters and a key ingredient for the reliable estimation of SM backgrounds to new physics searches. They also serve as an input to precision simulations in modern MC event generators for collider physics [5]. There has been significant recent progress in the computation of QCD radiative corrections [154–157]. Several groups have used different approaches to achieve the first $2 \to 3$ $\mathrm{N^{-2}LO}$ calculations of hadron collider processes. There have also been significant steps forward in the development of improved infrared subtraction schemes including methods to deal with higher-multiplicity processes at $\mathrm{N^{-2}LO}$. The computation of full SM corrections has seen major improvements as well [154]. A summary of the state of the art and targets for future measurements is shown in Table 6-10. The listed calculations correspond to the next frontier in cross section calculations for a multitude of processes, and their completion will elevate sensitivity of tests of the Standard Model and new physics searches at the HL-LHC by providing more accurate predictions for signal and background scattering processes. This Les Houches precision wish-list has served as a summary and repository for the higher-order QCD and EW calculations relevant for high-energy colliders, providing a crucial link between theory and experiment.

Strong coupling. The strong coupling, α_s, is a fundamental parameter of the SM and the least well known of its gauge couplings. The uncertainty on α_s will be one of the limiting factors in many measurements including Higgs couplings at the HL-LHC. BSM physics can also impact extractions of α_s in different ways and introduce tensions between their results. The relative uncertainty in the current world average, assuming no new physics or systematic discrepancies among extractions, is 0.8% and, within the next decade, can be reduced to $\approx 0.4\%$ (Table 6-11) [99]. This requires completing the necessary pQCD calculations and control of various commensurate factors to the same level. Many lattice QCD (LQCD) methods have been developed to extract α_s, and to provide systematic checks of these LQCD methods [158–161]. There are proposals to apply similar checks to phenomenological determinations [99, 162, 163].

Table 6-10. *Summary of the Les Houches precision wish-list for hadron colliders [154]. HTL stands for calculations in heavy top limit, VBF* stands for structure function approximation.*

process	known	desired
$pp \to h$	$\mathrm{N^3LO_{HTL}}$, $\mathrm{N^2LO^{(t)}_{QCD}}$, $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$(incl.), $\mathrm{N^2LO^{(b,c)}_{QCD}}$
$pp \to h + j$	$\mathrm{N^2LO_{HTL}}$, $\mathrm{NLO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{N^2LO_{HTL}}\otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to h + 2j$	$\mathrm{NLO_{HTL}}\otimes \mathrm{LO_{QCD}}$, $\mathrm{N^3LO^{(VBF*)}_{QCD}}$ (incl.), $\mathrm{N^2LO^{(VBF*)}_{QCD}}$, $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{N^2LO_{HTL}}\otimes\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{N^2LO^{(VBF)}_{QCD}}$
$pp \to h + 3j$	$\mathrm{NLO_{HTL}}$, $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to Vh$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO^{(t,b)}_{gg\to HZ}}$	
$pp \to Vh + j$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to hh$	$\mathrm{N^3LO_{HTL}}\otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to h + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{N^2LO_{QCD}}$ (off-diag.)	$\mathrm{N^2LO_{QCD}}$
$pp \to h + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to V$	$\mathrm{N^3LO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, + $\mathrm{NLO_{QCD}}$(gg)	$\mathrm{NLO_{QCD}}$ (gg, massive loops)
$pp \to V + j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$(QCD) , $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$(EW)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^\pm W^+W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, + $\mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 2\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 3\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to t\bar{t}$	$\mathrm{N^2LO_{QCD}}$ (w/ decays) + $\mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays, off-shell effects) $\mathrm{N^2LO_{QCD}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t} + j$	$\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$(w/o decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + 2j$	$\mathrm{NLO_{QCD}}$(w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + Z$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + W$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{N^2LO_{QCD}}$* (w/ decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to tZj$	$\mathrm{NLO_{QCD}}$+$\mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$(w/o decays)

Table 6-11. *Summary of current and projected future (within the decade ahead or, in parentheses, longer time scales) uncertainties in the $\alpha_s(m_Z)$ extractions used today to derive the world average of α_s [99].*

	Relative $\alpha_s(m_Z)$ uncertainty	
Method	Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	$<$ 1.%
(3) $Q\overline{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & global PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% ($<$ 1%)
(6) Electroweak fits	2.3%	($\approx$ 0.1%)
(7) Standalone hadron collider observables	2.4%	$\approx$ 1.5%
World average	0.8%	$\approx$ 0.4% (0.1%)

The FCC-ee, which combines 3×10^{12} Z bosons decaying hadronically at the Z pole, and a $\sqrt{s}$ calibration to tens of keV accuracy [164], would provide measurements with unparalleled precision. The FCC-ee extraction of $\alpha_s(m_Z)$ with 0.1% uncertainty [165] will enable searches for small deviations from SM predictions that could signal the presence of new physics contributions. Dedicated high-luminosity e^+e^- runs at the Z pole would also enable further precision tests of QCD through the study of the renormalization group running of the bottom-quark mass [166,167]. Future ep collider experiments would also provide many opportunities for precision determinations of α_s. The EIC [149,168] and EicC [169] will provide new high-luminosity data that could lead to a few percent uncertainty level [149]. The LHeC [151,152] would provide hadronic final-state observables covering a considerably larger range than was possible at HERA. It could determine α_s from inclusive DIS data alone, something not feasible with HERA data, and an experimental uncertainty possibly reduced to 0.2% [152].

Jet substructure. Quark- and gluon-initiated jets are used in measurements of α_s, the extraction of universal objects within factorized QCD, and for tuning parton-shower MC generators. They are statistically distinguishable due to their different fragmentation processes and can be separated using new tools such as jet substructure [135, 136, 170–175]. Charm- and bottom-quark jets, such as in the $h \to b\bar{b}$ and $h \to c\bar{c}$ final states, can be effectively separated from other jets due to the long lifetime of the heavy quark and the mass of the heavy-flavored hadrons [176–182]. Identifying these types of jets is a standard benchmark for development of new classical and machine learning-based jet taggers and can help enhance certain BSM signals [155, 183, 184]. Tagging has not realized its full potential due to large uncertainties in the modeling of gluon jets [183]. High purity samples of gluon jets provided by future lepton colliders through the process $\ell^+\ell^- \to h[\to gg]Z[\to \ell\ell]$ would significantly change this situation [143].

Jet substructure techniques are usually applied to identify Lorentz-boosted massive particles such as W, Z, h bosons, top quarks, and BSM particles in complex final states. Many collider scenarios also result in h, W, and Z bosons radiating off of very high energy jets ("Weak-strahlung"). There may also be top quarks produced via gluon splitting to $t\bar{t}$ within a jet that originates from light quarks or gluons. Identification of these signatures will be crucial for future high-energy colliders [137]. Unconventional signatures include cases where jets are composed of leptons and hadrons, only leptons, only photons, hadrons and missing transverse energy etc. In addition to the jet kinematics and substructure, the jet timing information [185] and other information can be used for classification. Examples include jets containing one or more hard leptons [186–190], displaced vertices [188, 191, 192], hard photons [193, 194], or significant missing transverse momentum [195, 196]. Some of these anomalous signatures are already starting to be explored at the LHC [197–201].

The jet substructure program has led to the introduction of techniques that systematically remove low-energy soft radiation [170–173, 202, 203] and can significantly reduce the dependence of observables on

non-perturbative QCD effects. For a generic infrared and collinear safe observable, one can measure its "groomed" counterpart, which will be infrared and collinear safe. Although these observables are theoretically cumbersome to compute, they can be very useful, for example for measurements of α_s.

Finer calorimeter granularity [204, 205], more hermetic coverage of tracking detectors, and precise timing information are expected to improve substructure measurements. In particular, at future Muon Colliders, such detectors in addition to detectors that specifically target the identification of particles originating from beam background, can reduce the impact of beam background on jet substructure observables.

New observables. Measurements of the flow of radiation, traditionally studied using event shapes or energy correlation functions, provide some of the most informative tests of QCD [206]. Energy correlators exhibit simple structures in perturbation theory [207–212]. Their measurements at future colliders would provide remarkable insights into the dynamics of jets and hadronization [206, 213].

Modern measurements rely strongly on the use of particle flow and tracking information. However, only observables that are completely inclusive over the spectrum of final states can be computed purely from perturbation theory. The non-perturbative input needed for theoretical predictions of track-based observables is universal and can be parametrized by so-called "track functions" [214, 215], which describe the fraction of energy carried by charged particles from a fragmenting quark or gluon. Recently it has been shown how to compute jet substructure observables at high precision by incorporating track functions [216, 217]. Such calculations give promise for precision jet substructure measurements at the HL-LHC. Track functions could be measured precisely at the ILC and other future e^+e^- colliders.

Table 6-12. *Top part: PDF-focused topics explored in Snowmass 2013 [218] and 2021 studies [134]. Bottom part: a selection of new critical tasks to develop a new generation of PDFs that meet the targets of the HL-LHC physics program.*

TOPIC	STATUS, Snowmass'2013	STATUS, Snowmass'2021
Achieved accuracy of PDFs	N^{-2}LO for evolution, DIS and vector boson production	N^{-2}LO for all key processes; N^{3}LO for some processes
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	LuXQED and other photon PDFs from several groups; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Small-x and threshold resummations implemented in several PDF sets
Available LHC processes to determine nucleon PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production at 7 and 8 TeV	$+\ t\bar{t}$, single-top, dijet, $\gamma/W/Z$+jet, low-Q Drell Yan pairs, ... at 7, 8, 13 TeV
Current, planned & proposed experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3, HL-LHC DIS: EIC, LHeC, MuIC, ...
Benchmarking of PDFs for the LHC	PDF4LHC'2015 recommendation in preparation	PDF4LHC'21 recommendation issued
Precision analysis of specialized PDFs		Transverse-momentum dependent PDFs, nuclear, meson PDFs
NEW TASKS in the HL-LHC ERA		
Obtain complete N^{-2}LO and N^{3}LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast N^{-2}LO interfaces	Estimate N^{-2}LO/N^{3}LO theory uncertainties	New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications

6.4.2 Non-perturbative QCD

Parton distribution functions in the nucleon. An overwhelming number of theoretical predictions for hadron colliders require PDFs [219–229], the non-perturbative functions quantifying probabilities for finding quarks and gluons in hadrons in high-energy scattering processes. PDFs contribute to precise measurements of the QCD coupling constant, heavy-quark masses, weak boson mass, and electroweak flavor-mixing parameters. PDFs often introduce the dominant source of uncertainty in collider experiments, such as in the CDF II high-statistics measurement of the W-boson mass [85]. Reducing these uncertainties requires continuous benchmarking and improvements of the theoretical framework [230,231]. The accurate knowledge of PDFs is also critical in searches for BSM interactions.

Table 6-12 illustrates the progress made on the PDF determinations since the previous Snowmass Summer Study in 2013 [218]. Details are presented in the Snowmass PDF whitepaper [134]. The N^{-2}LO QCD accuracy has become the standard for the modern nucleon PDFs, with N^{3}LO being on the horizon within the next decade. In addition, some PDF sets for precision physics include photon PDFs and QCD resummations. Current PDF predictions for parton luminosities agree within uncertainties at invariant masses $30 \lesssim m_X \lesssim 10^3$ GeV, relevant e.g. for Higgs and gauge-boson production, but in the gluon sector (gluon-gluon and gluon-quark parton luminosities), differences are seen at large masses [134]. These differences are a consequence of both methodology and data sets included in PDF fits. The available PDF ensembles account for a combination of experimental, theoretical, and methodological uncertainties [232] in different ways, and, as a result, the provided PDFs can differ. The PDF-dependent cross sections can differ as well by the amounts exceeding the missing N^{3}LO contributions.

The bottom part of Table 6-12 lists new tasks for the PDF analysis that emerge in the era of precision QCD. While the most precise N^{-2}LO or even N^{3}LO theoretical cross sections should be preferably used, the accuracy of the theoretical predictions in the fits also depends on other factors. For complex N^{-2}LO/N^{3}LO calculations, their fast approximate implementations (such as fast N^{-2}LO interfaces) must be developed. Propagation of correlated systematic errors into PDFs is a challenging task that requires combined efforts of experimentalists and theorists. Control of uncertainties requires, in particular, to either fit the experiments that are minimally affected by the unknown factors (for example, to include cross sections only on proton, rather than on nuclear targets), or to estimate the associated uncertainties from these factors directly in the fit. The PDF uncertainties must representatively reflect all PDF behaviors compatible with the fitted data [233]. PDFs must be developed for a wide range of users in a format that optimizes for accuracy, versatility, and speed across a broad range of applications — a highly non-trivial task.

Recent studies [149,234] provide projections using various techniques for the reduction of PDF uncertainties under anticipated near-future theoretical and experimental developments. As an illustration, the left panel of Fig. 6-25 compares the current PDF uncertainty for $gg \to h$ production and its reduction when simulated HL-LHC measurements are included in the conservative (scen A) and optimistic (scen C) scenarios, using PDF4LHC15 N^{-2}LO PDFs [75] as the baseline. The right panel shows an analogous projection for the reduction of the PDF uncertainty on the SM Higgs and $t\bar{t}$ cross sections at the LHC upon including the simulated measurements in DIS at the EIC, this time using the CT18 N^{-2}LO framework [225]. The ability of the LHC measurements to reduce the PDF uncertainty critically depends on the control of systematic effects. Deep inelastic scattering and hadroproduction at the EIC will constrain the PDFs for the LHC high-mass BSM searches most directly and without systematic or new-physics factors relevant at the LHC.

Predicting hadron structure in lattice QCD. As lattice QCD techniques advance in computations of PDFs from first principles, unpolarized phenomenological PDFs in the nucleon serve as important benchmarks for testing lattice QCD methods [235,236]. Namely, precisely determined phenomenological PDFs in the nucleon serve as a reference to validate lattice and non-perturbative QCD calculations. The combination of the observation-driven PDF analysis and lattice QCD is thus especially promising and drives related studies

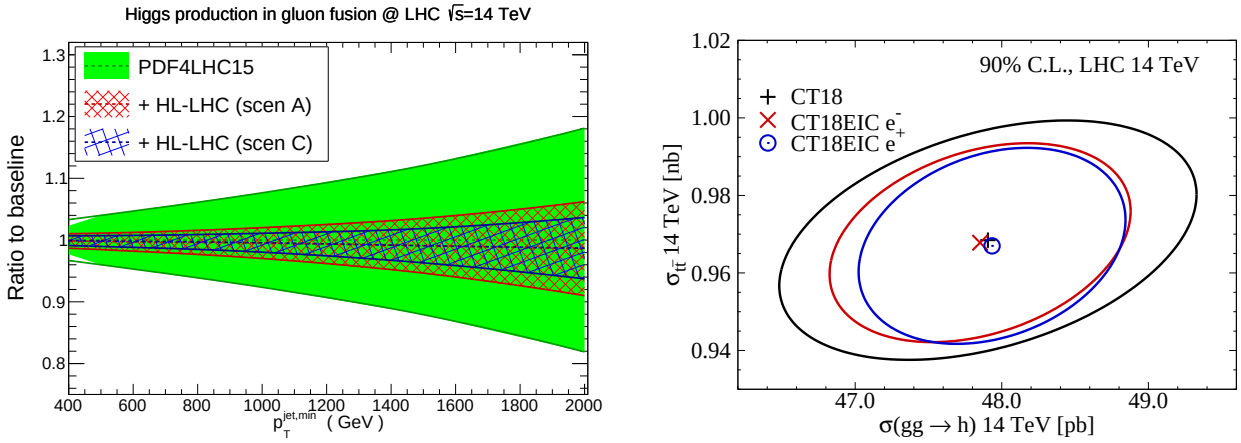


Figure 6-25. *Examples of projections for PDF uncertainties in the HL-LHC era. Left: Uncertainties for $N^{-2}LO$ Higgs production via gluon fusion at $\sqrt{s} = 14$ TeV obtained with published PDF4LHC15 $N^{-2}LO$ PDFs [75] (green band) and after additional constraints are imposed on these PDFs using simulated HL-LHC data in two scenarios (red and blue bands) [234]. Right: 90% CL uncertainty ellipses for $N^{-2}LO$ predictions for $gg \to h$ and $t\bar{t}$ production at the LHC with $\sqrt{s} = 14$ TeV obtained using CT18 $N^{-2}LO$ PDFs [225] and after imposing simulated constraints from inclusive DIS at the EIC [149].*

of three-dimensional structure of baryons and mesons, including dependence on transverse momentum and spin. Figure 6-26 (left) shows the impact of lattice QCD calculations on a quantity affecting precision measurements at hadron colliders — the difference between the strange quark and antiquark PDFs. Such novel calculations can significantly constrain quantities that are difficult to assess with conventional PDF estimates. Figure 6-26 (right) illustrates that recent lattice QCD calculations are now able to predict quark PDFs. Lattice QCD is most powerful in predicting various QCD charges and distributions of partons carrying 10% of the hadron's energy or more.

A Snowmass whitepaper [239] summarizes rapid advances in lattice QCD calculations of PDFs and other QCD functions. New experiments and facilities will pursue exploration of the three-dimensional structure described by transverse-momentum–dependent distributions (TMDs) as well as generalized parton distributions (GPDs) – hybrid momentum- and coordinate-space distributions that bridge the conventional form factors and collinear PDFs. These experiments will match the ongoing theoretical advancements that open doors to many previously unattainable predictions, from the x dependence of collinear nucleon PDFs to TMDs [240–244] and related functions [245–249], GPDs [250–253], and higher-twist terms – a progress that was not envisioned as possible during the 2013 Snowmass study.

There remain challenges to be overcome in lattice calculations, such as reducing the noise-to-signal ratio, extrapolating to the physical pion mass, and increasing hadronic boosts to suppress systematic uncertainties. Computational resources place significant limitations on the achievable precision, as sufficiently large and fine lattices are necessary to suppress finite-size and higher-twist contaminating contributions. New ideas can bypass these limitations. With sufficient support, lattice QCD can fill in the gaps where the experiments are difficult or not yet available, improve the precision of global fits, and provide better SM inputs to aid new-physics searches across several HEP frontiers.

Hadronization and fragmentation functions. Hadronization is a process of formation of detected final-state hadrons from partons. Governed by non-perturbative dynamics, hadronization cannot be calculated analytically and is elusive in lattice calculations. Accurate description of hadronization is, however, absolutely indispensable for predicting production of hadronic states.

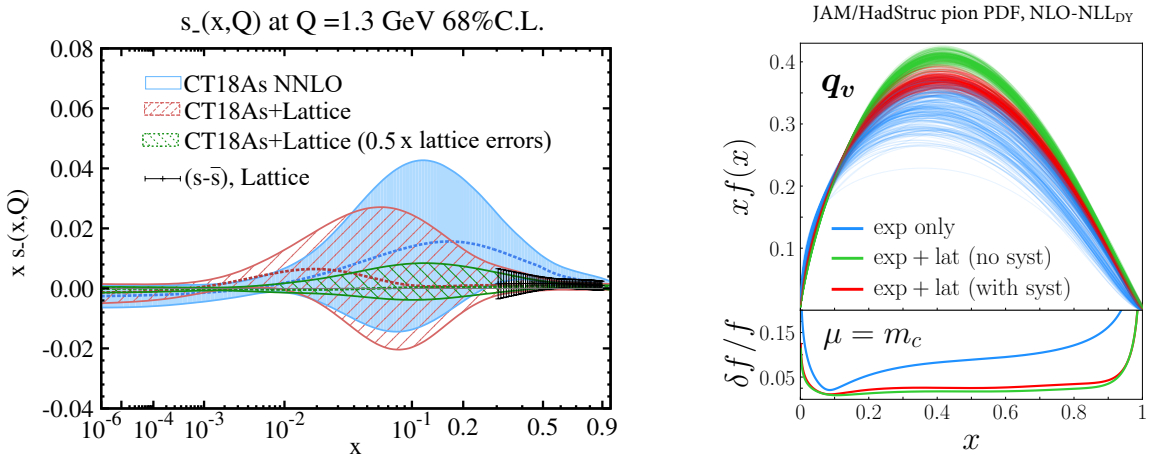


Figure 6-26. *Left: Impact of constraints from lattice QCD (black dashed area) on the difference between strange quark and antiquark PDFs in a CT18As $N^{-2}LO$ fit [237]. The red (green) error bands correspond to the current (reduced by 50%) lattice QCD errors. Right: determination of a quark PDF in a pion using a combination of experimental and lattice QCD data, and including threshold resummation [238].*

Fragmentation functions (FFs) – the probabilities for producing hadrons from fragementing partons – are instrumental for LHC experiments, as well as for extracting the spin-(in)dependent nucleon structure [254] at Belle II and the EIC. The Belle II program will emphasize investigation of full multidimensional dependency of FFs with complex final states, such as dihadrons or polarized hyperons, in order to map out their factorization universality properties and kinematic dependencies. Tagging on such final-state degrees of freedom allows more targeted access to the hadron structure in semi-inclusive deep inelastic scattering (SIDIS) experiments, e.g. at JLab and the EIC [255–258], where TMD PDFs and FFs will be the primary means to investigate the mechanism of hadronization in a 3D-picture [259].

Models of hadronization for the full event are necessary to predict background and signal processes in various BSM searches. Currently, modeling of backgrounds originating from light-quark fragmentation is mainly performed by MC event generators. Tuning those generators to a precision needed for discovery requires a model for correlated production of multiple hadrons that can only be verified with clean e^+e^- hadroproduction data. High-luminosity data of this kind from Belle II, combined with data at other energies from LEP and SLD, will provide a large lever arm in energy to confidently extrapolate the hadronization model from low to LHC energies and beyond.

Where neither the single-hadron FFs nor the MC event generators are sufficient to model multi-particle fragmentation, semi-analytical approaches to account for particle correlations gain more recognition. There have been significant recent efforts to define many-particle correlation observables that may obey factorization theorems, be sensitive to hadronization dynamics, can be interpreted within hadronization models (e.g. a QCD string model), and might be computed from QCD first principles in the future. Such correlation observables are already a focus at the LHC [260].

Accurate knowledge of FFs in e^+e^- collisions (especially, the gluon FF [261]) is of utmost importance for having an accurate "QCD vacuum" baseline to quantify "QCD medium" modifications of hadronization in proton-nucleus and nucleus-nucleus collisions [262, 263]. Looking toward the future, an FCC-ee would offer a clean radiation environment to systematically explore color reconnection, hadronization, and multiparticle correlations (in spin, color, space, momenta) — the non-perturbative final-state effects that currently rely on phenomenological MC modeling and may limit the ultimate accuracy at hadron-hadron colliders. In the *pp* case, the color reconnection effects may constitute 20–40% of the ultimately achievable uncertainty in

the measurement of the top mass [264] and can also impact limits in CP-violation searches in $H \to W^+W^-$ hadronic decays. At the FCC-ee, $e^+e^- \to W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ and $e^+e^- \to t\bar{t}$ processes, with the top quarks decaying and hadronizing closely to one another, would directly probe the color reconnection and interactions between hadronic strings [265–268].

6.4.3 Forward Physics

The LHC experiments opened access to a wide range of forward and diffractive processes, driving advances in relevant QCD theory, such as charting the gluon at very low x, revealing dynamics at high partonic densities, and testing MC models for forward hadron production. Understanding small-x dynamics in pp collisions, already important at the (HL-)LHC [127, 269], is crucial for any future higher-energy pp collider such as FCC-hh [270–273], where standard electroweak processes, e.g. W and Z production, are dominated by low–x dynamics, and an accurate calculation of the Higgs production cross section requires accounting for BFKL resummation [274–277] or partonic saturation [278].

Diffraction. Some configurations of final states with high forward multiplicities, as well as those with the absence of energy in the forward region (so-called rapidity gaps), in elastic, diffractive, and central exclusive processes originate from purely non-perturbative reactions, while others can be explained in terms of multi-parton chains or extensions of perturbative QCD such as the BFKL formalism. These processes are interesting for the exploration of electroweak and BSM physics. Understanding the elastic cross section and diffraction better, and probing models for Odderon [279–285] and Pomeron exchange, will be key studies at the HL-LHC, EIC, and any future hadron collider. Further progress in this fundamental area requires the combination of experimental measurements, including at the EIC and FPF, and theoretical work. The FPF also allows exploration of BFKL evolution and gluon saturation.

Physics opportunities at the CERN Forward Physics Facility. Given its unique configuration, the FPF [138, 158] would extend the coverage of the LHC measurements (notably, the LHCb) at small x by almost two orders of magnitude at low Q, reaching down to $x \simeq 10^{-7}$ (Fig. 6-27). In its proposed main configuration, the FPF will detect far-forward neutrinos, produced from charm meson decays in a main LHC detector, by DIS on a tungsten target. Therefore, FPF measurements would provide a bridge between the physics program at the HL-LHC and that of a higher-energy pp collider. Successful interpretation of FPF measurements will require a coordinated program including forward production at LHCb [286–289], large-x charge current DIS at EIC [149], and small-x scattering at the HL-LHC and future DIS facilities such as the Muon-Ion Collider [150] and LHeC [152]. In turn, with future experiments designed to detect neutrino interactions with energies between several hundreds of GeV and a few TeV, an energy range that has not been precisely probed for any neutrino flavor, the FPF will significantly extend accelerator cross section measurements and will provide improved predictions for key astroparticle physics processes, such as ultra-high energy neutrino-nucleus and cosmic ray interaction cross sections.

Figure 6-27 also demonstrates that the FPF will be sensitive to very high–x kinematics and in particular the intrinsic charm component of the proton [290]. While charm production in pp collisions is dominated by gluon–gluon scattering, in the presence of a non–perturbative charm PDF in the proton, the charm-gluon initial state may be dominant for forward D-meson production. FPF measurements, as part of a broader physics program including LHCb and the EIC, would provide complementary handles on high-x intrinsic charm. At the small-x end, FPF observations would reduce the currently large uncertainties on the expected flux of prompt neutrinos arising from the decays of charm mesons produced in cosmic-ray collisions in the atmosphere [291–294]. These represent an important background for astrophysical neutrinos at neutrino telescopes such as IceCube [295] and KM3NET [296].

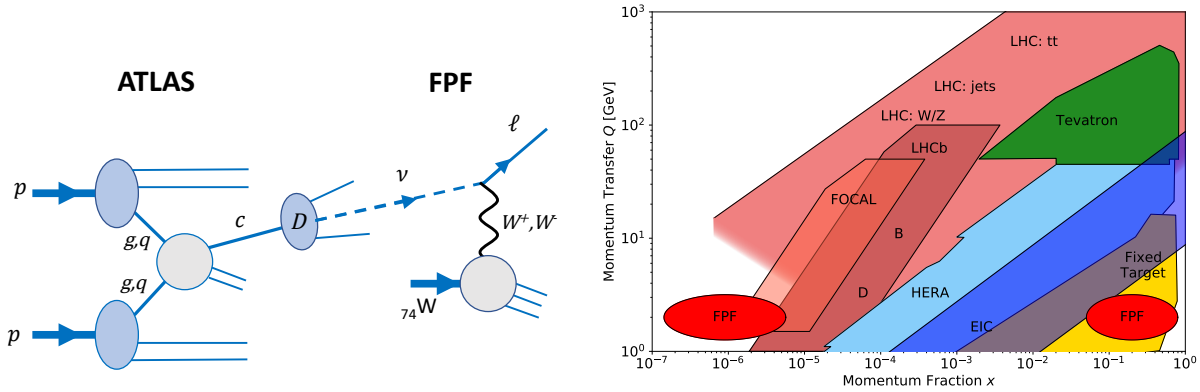


Figure 6-27. *Left: The production and detection processes for forward D-meson production at the HL-LHC followed by their decay into neutrinos falling within the FPF acceptance. Right: The (x, Q) regions (red ovals) that can be accessed at the FPF via this process.*

Neutrino-induced deep inelastic scattering (DIS) mediated by charged current (CC), such as that at the FPF, provides essential flavor separation in global PDF fits [297] that is not achieved solely in neutral-current (NC) DIS. Hence FPF data can complement other planned experiments, such as the EIC. The coverage for CC DIS on nuclei at the FPF in Fig. 6-27 broadly overlaps with that for charged-lepton CC DIS at the EIC [149, 298]. Analogous information from previous neutrino-induced DIS measurements on nuclear targets (NuTeV [299], NOMAD [300], CCFR [301], CHORUS [302]) plays the key role in global PDF fits of nucleon and nuclear PDFs (with the two related via nuclear corrections). Inclusive CC DIS and, especially, semi-inclusive charm production in CC DIS are the primary channels to probe the PDFs for strange quarks and antiquarks. The strange-quark PDF offers insights about the non-perturbative proton structure [303], while it also drives much of the PDF uncertainty in W boson mass measurements at the LHC [304]. On the experimental side, determination of the (anti-)strangeness PDF has been a hot topic, as the different experimental results somewhat favor different shapes for $s-$quark PDFs [225, 305–307]. The elevated PDF uncertainty from fitting such inconsistent experiments propagates into various pQCD predictions [99, 134, 308].

6.4.4 Heavy Ions

The relativistic heavy-ion (HI) program prioritizes the studies of the quark-gluon plasma (QGP), the partonic structure of nuclei, collectivity in small collision systems [309–313], and nuclear electromagnetic (EM) interactions [314,315]. The HI studies have been a valuable part of the LHC physics program, with a variety of cross-cutting connections to the other areas of LHC physics summarized in Sec. 6.4.5. Reference [316] presents a detailed plan for the HI measurements at the HL-LHC. These measurements will greatly benefit from planned detector upgrades for ALICE, ATLAS, and CMS. ALICE FoCal, a forward calorimeter that will allow us to probe parton distributions down to lower Bjorken-x values than are previously accessible [317]. The increased pseudorapidity acceptance of charged particle tracking will be a boon to bulk particle detection. The upgraded Zero Degree Calorimeters (ZDCs) [318, 319] will improve triggering and identification for ultraperipheral collisions (see Sec. 6.4.5). The addition of time-of-flight particle identification capability in the CMS timing detector [320] will allow differentiation among low-momentum pions, kaons, protons, and charmed states. The planned major upgrade of the ALICE detector for HL-LHC Run 5 (ALICE 3 [321]) will enable far-reaching studies of the QGP properties. The HL-LHC HI program is synergistic with the

HI programs at RHIC and the EIC. The sPHENIX detector [322–324] at RHIC will start HI data-taking in 2023 with the aim to collect quality heavy-flavor meson, quarkonium, and jet data in Au-Au collisions.

Hard probes. High momentum-transfer interactions between partons in the nuclear medium serve as short-distance probes of the QGP. They can reveal the impact of QGP on color charges of fast-moving partons or slow-moving heavy quarks, commonly resulting in the attenuation of the jets [325–338], or modifications of the jet substructure [339–351], referred to as jet quenching. ALICE, ATLAS, and CMS measurements will significantly reduce statistical and systematic uncertainties in key measurements of medium modification of light or heavy quark jets produced in association with γ, Z, or D^0 [324,352]. Studies of medium dependence of jet quenching at the HL-LHC would be facilitated by collecting large pp samples of events with the same signatures and low pileup. By comparing the LHC and RHIC data, we aim to constrain the temperature dependence of the transport coefficients of QGP.

The main HL-LHC experiments will also increase capabilities for detection of heavy-flavor (HF) mesons [353–361] and quarkonia [362–369]. Heavy quarks, c and b, are unique, slow-moving QGP probes produced during the early stages of the hard collision. In the medium, they radiate less energy than light flavors due to the dead-cone effect. Observations of HF mesons elucidate mechanisms for their thermalization, Debye color screening and recombination [370–372] inside the QGP. Measurements of the p_{T} dependence of the quarkonium nuclear modification factors (R_{AA}) will discern whether high-p_{T} quarkonium formation is driven by the Debye screening mechanism or by energy loss in the medium [373]. Improved elliptic flow measurements of charm mesons in p-Pb [374] and of HF decay muons [375] and $\Upsilon(1S)$ [373] in Pb-Pb collisions will provide insights both on the degree of thermalization of HF quarks at low p_{T} and on the recombination of bottomonia from deconfined b quarks in the QGP. Production of strange B mesons and charm baryons in pp and Pb-Pb collisions [373] will investigate the interplay between the predicted enhancement of strange quark production and the quenching mechanism for beauty quarks, and on the contribution of recombination of HF quarks with lighter quarks to hadronization in HI collisions. Precise measurements of beauty mesons in p-Pb collisions [373] will help to establish the relative contributions of hadronization and nuclear-matter effects. Interpretation of these HL-LHC observations will be facilitated by the sPHENIX measurements of HF hadron spectra, particle multiplicities, and azimuthal anisotropy at lower energy, allowing especially to strongly constrain the HF diffusion coefficient and its temperature dependence.

Hadronic structure. Abundant production of light (anti-)nuclei at ALICE opens promising opportunities. As in the cases of light nuclei and charmonium, the statistical hadronization or coalescence assumption can render a unique insight into the structure (e.g. tetraquark or molecular state) of exotic hadrons, such as $X(3872)$ studied by LHCb in high-multiplicity pp collisions [376] and by CMS in Pb+Pb collisions [377]. Those initial measurements will be followed up with high-statistics data in LHC Runs 3 and 4. In LHC Run 5, the ALICE 3 detector would precisely measure multi-charm baryons, expanding the hadronization studies in Runs 3 and 4. ALICE 3 would be a perfect tool to study the formation of light nuclei, hyper-nuclei, super-nuclei, and properties of exotic states, e.g. $X(3872)$ and the newly discovered T_{cc}^{+}.

Collectivity of small and large systems will be studied with high-statistics samples of pp, pPb, and PbPb events at the HL-LHC. The pivotal upgrades of ATLAS and CMS trackers will extend observations of charged particles to a wide pseudorapidity range ($|\eta| < 4$). For small systems, we expect a crucial improvement in the determination of the created system's size by measuring the Hanbury-Brown-Twiss (HBT) radii [375]. Azimuthally-dependent femtoscopy will measure the spatial ellipticity of the medium at freeze-out, e.g., to find the normalized second-order Fourier component of the transverse HBT radius as a function of the flow's magnitude. The extended η acceptance in Run 4 will refine the characterization of the rapidity dependence of factorization breaking. Better measurements of the forward-backward multiplicity correlation and multi-particle cumulants will deepen our understanding of the early-stage medium fluctuations [375].

6.4.5 Cross-Cutting QCD

Successes across many areas depend on future developments at the intersections of QCD and other domains. To take advantage of precise perturbative QCD calculations, commensurate advances must be achieved in accuracy of long-distance QCD and electroweak contributions, event generation, error analysis. These tasks require collaborations of experimentalists and theorists, model-builders and QCD experts, and, more broadly, support for the *QCD infrastructure* that adapts theoretical tools for experimental analyses according to standard protocols. This subsection presents examples of such cross-cutting issues from the QCD physics report [17].

Comprehensive uncertainty estimates. Measurements of the W-boson mass and other LHC precision observables are affected by many systematic uncertainties arising from both the experimental and theoretical sides. NNLO PDFs used in many analyses are sensitive to modeling of experimental systematics that is not under full control in the PDF fits [134]. Accuracy of PDFs can be increased if experimental groups publish more complete models of systematic uncertainties [378]. To estimate these uncertainties, high-order calculations for complex final states must be adapted to be fast and practical [379–381]. New types of complexity issues emerge in comparisons of multiparametric models with many parameters to very large data samples expected at the LHC Run 3 and HL-LHC. Undetected biases due to non-representative exploration of contributing systematic factors must be watched for, as has been recently demonstrated on an example of a PDF global fit [233]. Figure 6-28 illustrates that elevating the accuracy of QCD calculations to one percent requires both individual precise theoretical calculations as well as accurate supporting theoretical infrastructure that would allow to explore exhaustively the relevant systematic factors. Reaching this target also requires agreed-upon standards and practices for accuracy control at all stages of the analyses.

QCD in new physics searches and SMEFT fits. The energy reach of many BSM searches at the HL-LHC depends on the interplay between precision calculations of matrix elements and PDF analyses. At masses above a few TeV, production of BSM particles requires large momentum fractions x, where PDF uncertainties remain large due to a mix of influences from low statistics, nuclear corrections, higher-twist contributions, intrinsic heavy-quark components. Either forward particle production at the LHC or, often more cleanly, DIS at the EIC can constrain PDFs in the large-x region relevant for the TeV mass range.

Searches for deviations from SM examined in the language of EFT (e.g. SMEFT analyses) is an active research area (see Sec. 6.3.4.2 and EF04 report [16]). Although the proton structure parametrized by PDFs is intrinsically a low-energy input and should in principle be separable from the imprints of SMEFT operators, the complexity of the LHC environment might intertwine them [382, 390–394]. As illustrated in the left Fig. 6-29, fitting the SMEFT coefficients and PDFs together generally results in different constraints than when the fixed PDFs are used. Constraints on either the PDFs or EFT operators in low-energy experiments,

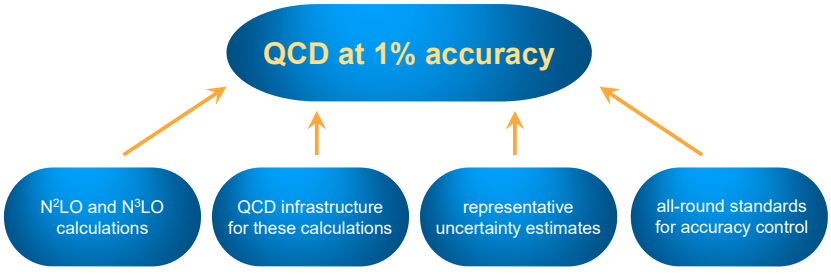


Figure 6-28. *Prerequisites for achieving percent-level accuracy in QCD calculations.*

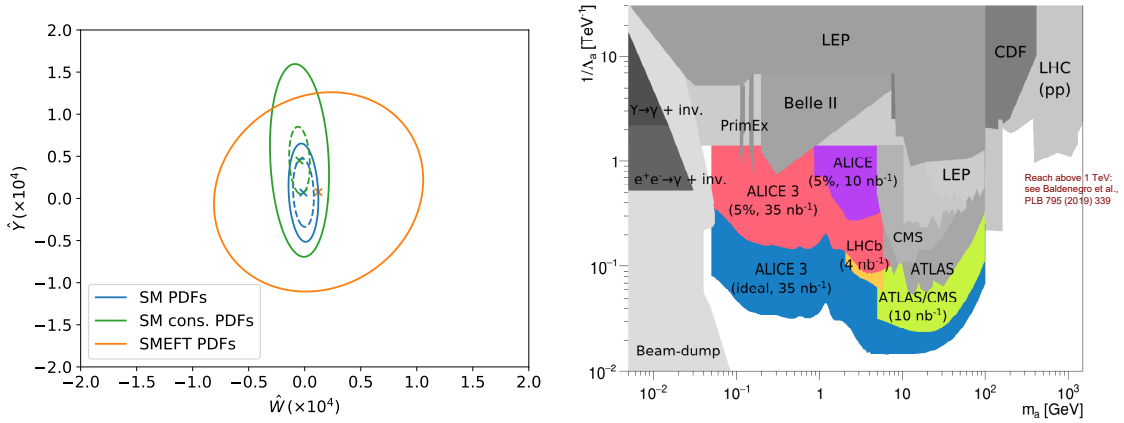


Figure 6-29. *Left: The 95% confidence level bounds on the plane of the Wilson coefficients considered in Ref. [382] obtained using either fixed SM PDFs (blue) or conservative SM PDFs that do not include high-energy data (green). PDF uncertainties are included in the solid lines and not included in the dashed lines. Results are compared to those obtained in a simultaneous fit of SMEFT and PDFs, when the PDFs are allowed to vary when varying the values of the Wilson coefficients (orange). Right: Compilation of exclusion ALPs limits obtained by different studies [316, 383, 384], with limits from $\gamma\gamma$ scattering at ATLAS [385], CMS [386], the projected performance with ALICE 3 detector [387], and exclusive $\gamma\gamma$ production with tagged forward protons at ATLAS and CMS-TOTEM [388, 389].*

such as the EIC, where some or all new physics contributions are absent, can be crucial for disentangling the SM/BSM degeneracies at the (HL-)LHC, especially for spin-dependent EFT operators [395, 396].

Ultraperipheral ion collisions (UPCs) are electromagnetic interactions of relativistic heavy ions, occurring when the nuclei pass by with impact parameter $b > 2R_A$, where R_A is the nuclear radius [397, 398]. UPCs are energy-frontier for collisions associated with photons since these photon fields around ions interact with the opposing nucleus, in a photonuclear interaction, or with each other, in a $\gamma\gamma$ collision. Quantitative predictions for exclusive processes and/or small momentum fractions probed in the UPCs require coordinated advancements in perturbative QCD, nuclear, and electroweak theory, serving as an example of cross-cutting connections. In addition, the UPCs can be used to search for BSM phenomena. ALICE, ATLAS, and CMS have a suite of planned measurements of photonuclear reactions with upgraded detectors. LHCb is well positioned for exclusive production studies in UPCs in the forward direction. Exclusive photonuclear production of vector mesons, jets, and heavy quarks at the highest center-of-mass energies yields a tool to study nuclear parton densities (especially the gluon density) at momentum fractions down to $x \gtrsim 10^{-6}$, where saturation may be most pronounced []. The expected performance at HL-LHC and the future plan have been detailed in Refs. [399, 400]. In the $\gamma\gamma$ mode with tagging on two intact initial hadrons, the LHC can reach unprecedented sensitivities to quartic anomalous couplings, such as $\gamma\gamma\gamma\gamma$, $\gamma\gamma WW$, γZZ, $\gamma\gamma\gamma Z$, $\gamma\gamma t\bar{t}$ only to quote a few [389, 401–408]. The final states in $\gamma\gamma$ interactions at the LHC are remarkably clean (like at LEP), resulting in sensitivities to quartic anomalous couplings and to the production of axion-like particles (ALPs) at high masses that is better by 2-3 orders of magnitude than in usual LHC searches. Figure 6-29 (right) illustrates the sensitivity to ALPs in *pp* and heavy-ion interactions at the LHC, with the coupling plotted as a function of the particle's mass [384]. Finally, the production of an electron and muon pairs via $\gamma\gamma$ interactions are of great interest since they give access to τ pairs, which are sensitive to BSM physics, including τ dipole moment, lepton compositeness or supersymmetry [409].

Detectors and QCD theory for hadron colliders. Detectors for a possible 100 TeV hadron-hadron collider must implement innovative designs to achieve the necessary precision when measuring the SM

processes, while also precisely reconstructing multi-TeV physics objects. They should be able to seek massive hyperboosted objects inside highly collimated hadronic jets and to deal with a factor-of-five larger pileup than at the HL-LHC. In theoretical predictions, a predictive BFKL-like QCD formalism will be necessary to quantify parton scattering at momentum fractions as low as 10^{-7}. Electroweak gauge bosons W and Z, leptons, and top quarks will be copiously produced in a mix of QCD and EW interactions and will need to be included into the PDFs together with quarks and gluons [410]. Detailed studies of hadronic and electromagnetic showers will be needed in the next few decades to achieve the best predictions at future hadron collider energy and luminosity.

6.5 The physics beyond the Standard Model

There are abundant reasons why physics beyond the SM of particle physics is likely and, in some cases, unavoidable. Such reasons are connected to the fundamental questions that lie at the core of the energy frontier program, as we discussed in Sec. 6.1, answering which is among the highest priorities of particle physics. Current and future experiments at the energy frontier offer unique capabilities to explore many of these questions.

In this context, energy frontier explorations follow three main leads:

1. Studies of phenomena that have been observed but for which a fundamental explanation is still lacking. These include:
   - What is the fundamental composition of Dark Matter?
   - What is the additional source of CP violation needed to explain the matter-antimatter asymmetry observed in the universe?
   - Possible observations of BSM physics referred to broadly as *Anomalies*.
2. Following guiding principles forming the basis of the successful stories behind the SM and, more generally, of modern theoretical physics. These may offer us insight on where the theoretical framework is "hinting" for a more complete description of Nature, such as:
   - Naturalness.
   - The structure of flavor.
3. Search for possible new phenomena that might not fit in the simplest theoretical extensions of the SM and for which, as history has shown many times, particle physics should maintain a wide open view for. This includes addressing questions like:
   - Are there new interactions or new particles around or above the electroweak scale?
   - Is lepton universality violated?
   - Are there long-lived or feebly-interacting particles which have evaded traditional BSM searches?
   - Broadly speaking, how can we reduce biases in our searches and conduct them in a more model-independent way?

Two main theoretical approaches in exploring BSM physics can be commonly identified. The first consists in seeking self-consistent theories that aim to address the questions above and can significantly boost our understanding of the fundamental laws of Nature. These well-motivated models of BSM physics, such as

SUSY and Composite Models, are self-consistent to high-energy scales, and are excellent test cases for exploring possible experimental signatures and their interrelation. Looking beyond these prominent models, the landscape of possible experimental and theoretically-motivated models and signatures is very large. In this approach, well-defined but incomplete theories extend specific areas without the expectation of full self-consistency. These *simplified* models or *portal* models are in some cases simplifications of complete theories. It is not practical nor useful to try to be exhaustive in projecting the scientific output of projects targeting all such models. Instead, we focus on a representative set of models and signatures that are deeply connected with the fundamental questions above and represent a wide range of physics that can be explored at the energy frontier. Such an approach has the advantage of providing a manageable framework where different experimental results can be easily compared and, eventually, mapped into the parameter space of complete theories. However, the drawback is that those have intrinsically a larger degree of arbitrariness and should be viewed as simpler guiding frameworks for the more general exploration of BSM physics.

In this section, we summarize and chose a few representative benchmark models and scenarios from the BSM Topical Group report [18]. These benchmarks include DM-driven considerations, as well as exciting recent development on long-lived particles. We discuss their implications for the current and future collider programs.

6.5.1 Composite Higgs Models

Determining whether the Higgs boson is an elementary or composite particle remains a fundamental open question. The idea of a composite Higgs boson is attractive because it avoids the theoretical challenges associated with explaining the relatively small mass of a fundamental scalar particle. A composite Higgs boson requires a new strong gauge interaction whose coupling becomes strong above the TeV scale and binds together new elementary constituents. These constituents inevitably form not only the Higgs boson, but also many other bound states, much like the structure seen with QCD dynamics. In such models, the Higgs boson is the lightest bound state similar to the pion of QCD, protected by an approximate global symmetry, and observing other heavier resonances above the Higgs boson mass at the compositeness scale would be a tell-tale sign of Higgs compositeness. Current searches generically constrain the lowest lying resonances to be heavier than the TeV scale with lower mass limits in the range of 1-3 TeV for resonances with spin 1/2, 1, and 2. In addition to the direct production of new resonances, Higgs compositeness would also cause deviations in the couplings of the Higgs boson to gauge bosons and the (composite) top quark. These deviations are inversely proportional to the scale of compositeness and therefore require precision measurements for detection.

The phenomenology of Composite Higgs models is mainly governed by two parameters: the mass (compositeness) scale m_* and the coupling g_*, which sets the scale of the couplings in the EFT Lagrangian. The strongly interacting model is expected to have $g_* > 1$ couplings, while unitarity requires $g_* < 4\pi$. The Wilson Coefficients, defined in Ref. [42], can be all parameterized in terms of this mass scale and coupling, modulo order 1 factors. Different colliders have complementary sensitivities to the various operators (C_ϕ, C_{2w}, C_w); these are summarized in the BSM Topical Group report [18]. Sensitivity to a toy Composite Higgs model from several future colliders is shown in Fig. 6-30. Curves from HL-LHC, FCC-ee/eh/hh, and CLIC are taken from Ref. [412]. Each Wilson coefficient has a different mass-dependence of the coupling sensitivity. Sensitivity to C_ϕ arises primarily through precision measurements of Higgs couplings; sensitivity to C_{2w} arises from measurements of high energy Drell-Yan events; and sensitivity to C_w more broadly comes from electroweak precision fits. Also shown is the direct search sensitivity for a triplet vector ρ resonance at FCC-hh. The sensitivity from the 10 TeV Muon Collider is taken from studies of the tree level process $\mu^+\mu^- \to hh\nu\overline{\nu}$ [81], which provides good sensitivity for C_w and C_{2w}, but not C_ϕ. Sensitivity to C_ϕ from

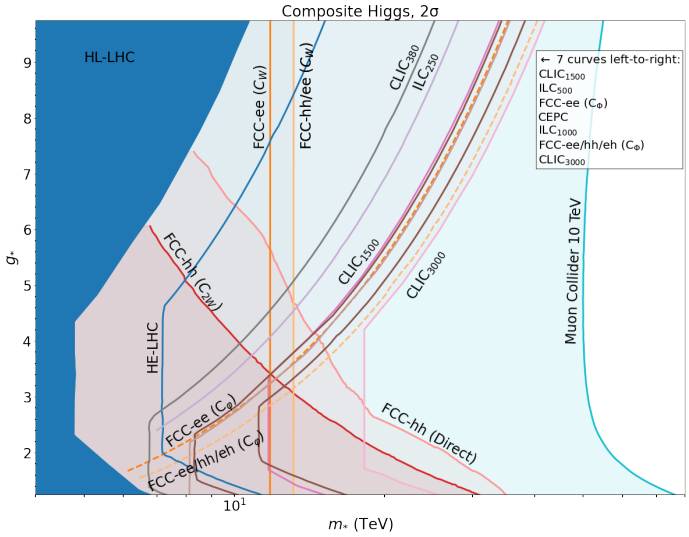


Figure 6-30. *Exclusion (2-σ) sensitivity projections for future colliders. Plot based on Refs. [81, 411].*

Higgs coupling measurements at a Muon Collider [413] are expected to be competitive, but are not shown here. We can also see the complementarity between direct resonance searches and the precision measurements on the SMEFT operators in this figure. This implies that if future discoveries point to signals of composite models, we will be able to use a whole class of operators to interpret other direct searches and pin down the underlying theory.

6.5.2 SUSY Models

Supersymmety (SUSY) is a symmetry that extends the SM fields by adding a set of partner fields with the same Yukawa couplings and gauge quantum numbers but different spins. An extended Higgs sector is also required for SUSY. The motivations for this symmetry include that it results in the unification of gauge and Yukawa couplings at high energies, radiative effects directly lead to electroweak symmetry breaking, and in some versions it naturally contains a DM candidate. Furthermore SUSY appears in low-energy realizations of grand unified theories and superstrings, that allow for a consistent quantization of gravity. SUSY, however, cannot be an unbroken symmetry of nature, because particles with the same mass but different spin are not observed. Instead SUSY is assumed to be broken by a set of soft SUSY-breaking terms. These terms govern the masses of the predicted SUSY partner particles.

There are many specific models within the SUSY framework. The sensitivity studies presented here focus on R-parity conserving decays in the minimal supersymmetric standard model (MSSM). In the MSSM, there is a lightest supersymmetric particle (LSP) which is protected from decay by R-parity and therefore contains a dark matter candidate. There are many other models including those that violate R-parity in different ways, and the next-to-MSSM (NMSSM) which includes an additional singlet to dynamically generate the dimensionful μ-term.

The Higgs-boson mass in the MSSM is strongly constrained but receives logarithmic corrections due to stop-squark loops. To achieve the observed Higgs mass, these loops need to be above order 1 TeV which is the

scale just being reached by the LHC (see Fig. 6-31). Conversely, for a small mixing between the two stop squarks and $\tan\beta \gg 1$, the stop-quarks mass can be at most 5-10 TeV [414].

This wide variety of phenomena and the fact that it is widely studied make the MSSM a good context to make comparison plots between different collider scenarios. Figure 6-31 shows the comparative sensitivity in the MSSM for a representative set of key points in the model space. It includes large mass splittings for stop squarks, which are strongly produced, and two example weakly-produced scenarios. The first weak production example is a classic Wino-Bino model with large mass splitting, and the second is a Higgsino model with a small mass splitting motivated by naturalness considerations. The relevance of these plots goes beyond the SUSY context. The relative sensitivity to weak and strong, large and small mass-splittings are representative of what sensitivity might be observed in other models with new states. The studies focus on R-parity conserving SUSY where there is a stable lightest-supersymmetric state that is only weakly interacting. This is a challenging scenario, particularly for hadron colliders which have pile-up effects, a range of parton-collision energies, and reduced resolution and information about the momentum conservation in the beam direction, however there are some R-parity-violating and other scenarios which are at least as challenging and remain significantly unconstrained by the LHC. The plot show the 95% exclusion limits. For discovery, the sensitivity at a hadron collider would be lower, while at a lepton collider it would be quite similar.

The range of possible SUSY models is vast. Even within the MSSM, there are many parameters and the complex interplay can lead to different signatures. One way to understand this complex space is to construct a Monte Carlo scan over the parameter space. For this purpose, a good candidate is the pMSSM, which reduces the 120-parameter MSSM space to 19 free parameters, specified at the EW scale, based on assumptions related to current experimental constraints (including those from flavor, CP violation, and EW symmetry breaking) rather than details of the SUSY breaking mechanism. Then with the scan points, the masses of particles, the relevant couplings, and impacts on precision measurements, rare processes, and cosmology can be studied.

Figure 6-32 shows the dependence of the $h(125) \to b\bar{b}$ branching fraction on the mass of the psuedo-scalar Higgs m_A and $\tan\beta$, the ratio of the up and down vacuum expectation values [417]. The branching fraction is reported in terms of the coupling modifier κ_b (ratio to the SM coupling). The plot shows the fraction of pMSSM scan points with κ_b within 1% of the SM expectation of unity, where the range of 1% is chosen to approximately reflect the 95% CL corresponding to the 0.48% precision on κ_b expected from a combination of precision measurements at FCC-ee, FCC-eh, and FCC-hh [42]. Expected 95% CL exclusions from direct searches for pseudoscalar Higgs boson (A) at the HL-LHC and FCC-hh are overlaid for reference; points to the left of the lines are excluded. Exclusions at low $\tan\beta$ are obtained from studies of $A \to bb/tt$ [418], and those at high $\tan\beta$ come from projections for $A \to \tau^+\tau^-$ [30, 418]. As is evident in the plot, direct searches for A at the HL-LHC are expected to provide better sensitivity to the MSSM than the highest precision measurements of κ_b, which shows the strongest MSSM-related deviation of any Higgs coupling parameter.

6.5.3 New Bosons, Heavy Resonances, and New Fermions

Direct searches for new states beyond specific models provide vital information in our explorations for new physics. The new states could appear as heavy resonances, such as new bosons and new fermions, well-motivated from the model-building perspectives. In this section, we chose the case of new bosons as an example. Various representative examples of studies for current and future facilities are discussed in the BSM Topical Group report [18]. New heavy vector bosons are often regarded as the standard candle for BSM searches. The canonical example is a Z' boson, which is a neutral vector particle coupling to a SM fermion and antifermion. From the phenomenological perspective, Z' searches are generally characterized by the

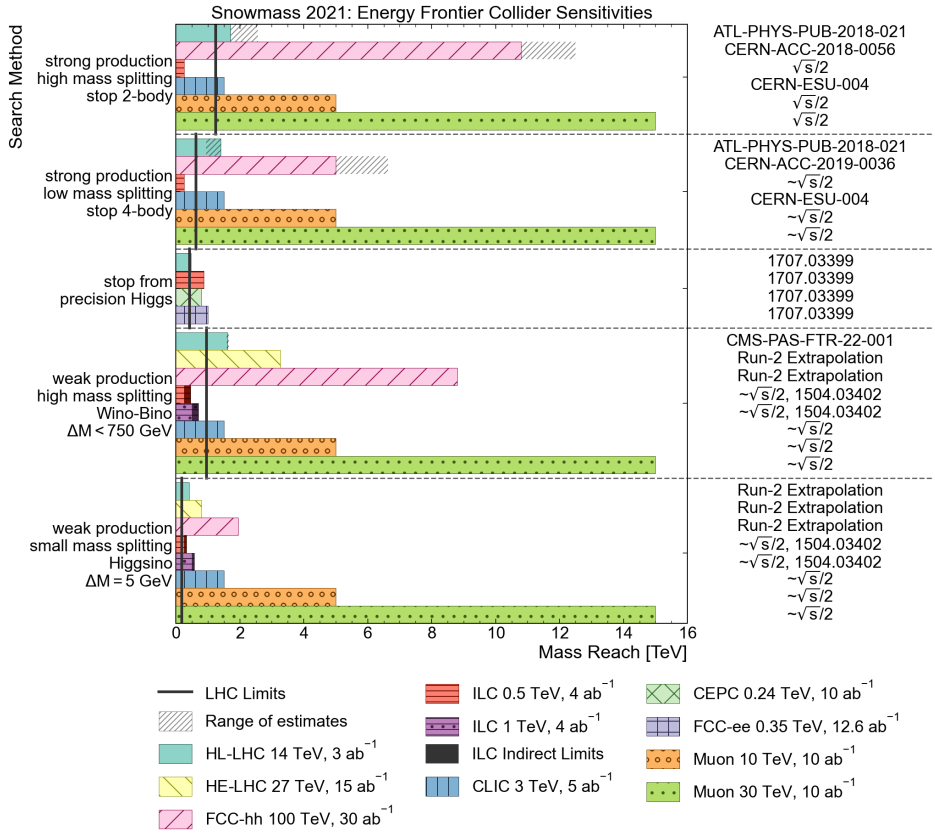


Figure 6-31. *Comparison of 95% exclusion SUSY sensitivities at different colliders for a representative set of scenarios, including small and large mass splittings for stop squarks, which are strongly produced, a large mass splitting Wino-Bino model, and a small mass splitting Higgsino model. The limits come from a combination of dedicated studies and extrapolations based on the collider reach program [415]. The hashed gray band indicates the range of estimates in the case where both a dedicated study and Run-2 extrapolation are available. Current expected limits from the LHC are shown as vertical lines. For the ILC limits (also relevant for other e^+e^- colliders, not shown) there are indirect constraints from precision $e^+e^- \to f\bar{f}$ measurements [416]*

production coupling, the decay coupling, and the resonance mass, where the decay coupling is typically traded for the branching fraction to the desired final state. A coupling vs. mass framework for Z' searches [419, 420] helps distill the Z' resonance signal from disparate ultraviolet models into the minimal new physics parameter space relevant for resonance searches at colliders. This framework also enables direct comparison of experimental reach across different collider proposals, including a comparison of e^+e^-, pp, and $\mu^+\mu^-$ colliders as well as other collider options.

Two specific Z' models studied in the many Snowmass 2021 contributions include the universal Z' model and the Sequential Standard Model (SSM). The universal Z' model features a Z' boson with unit charges for all SM fermions, hence its universal designation. The sequential standard model (SSM) Z' boson follows the same coupling pattern of the SM Z boson, and is the benchmark model most commonly used by experimental searches. Figure 6-33 compares the sensitivity to a universal Z' at different colliders [411, 421]. Included in the figure are new Snowmass 2021 results for the Muon Collider: it shows that a Muon Collider at $\sqrt{s} = 3$

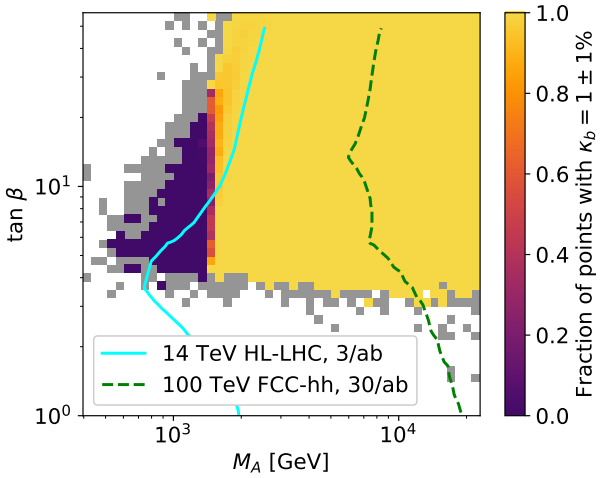


Figure 6-32. *The fraction of pMSSM scan points with κ_b within 1% of the SM expectation of unity as a function of $\tan\beta$ and M_A. The range of 1% is chosen to approximately reflect the 95% CL corresponding to the 0.48% precision on κ_b expected from the FCC-ee/eh/hh combination [42]. Expected 95% CL exclusions from HL-LHC [30, 418] and FCC-hh [418] are overlaid for reference. White bins include no scan points generated by the Markov chain Monte Carlo (McMC) procedure. Gray bins include scan points generated by the McMC, but rejected at a later step because of lack of consistency with current precision measurements and direct searches.*

TeV is competitive with other colliders, with sensitivity nearly identical to ILC at $\sqrt{s} = 1$ TeV. A Muon Collider at $\sqrt{s} = 10$ TeV has the highest mass reach for a universal Z' with large couplings $g_{Z'}$, probing masses $M_{Z'} > 100$ TeV, although only indirectly. A Muon Collider at $\sqrt{s} = 10$ TeV is sensitive to smaller couplings than the other colliders, with the exception of FCC-hh, which has the highest sensitivity from direct searches within the mass region $M_{Z'} < 28$ TeV but can directly probe up to about 45 TeV. In this respect the FCC-hh and a 10-TeV Muon Collider will play a very complementary role. Lepton colliders have an edge in sensitivity when the boson is so heavy that only indirect effects can be measured, arising from the fact that in the signal kinematic distributions the lepton collider experiments benefit from relatively smaller systematic uncertainties. We can also see in this figure the complementarity between direct resonance searches and precision measurements of the SMEFT operators. Direct resonance searches allows us to go to small couplings within accessible energies at lepton colliders. Series of chiral determination of the BSM interference effects can also enable us to extract the new resonance's interaction structure [33, 422, 423].

All the different Snowmass contributions related to this topic can be organized into a summary table, see Table 6-13, to enable an illustrative comparison between the various Z' models and current and possible collider scenarios. To enable the comparison and focus on the mass reach of the different colliders, we adopted the $g'_Z = 0.2$ coupling parameter for the universal Z' model, since it roughly aligns with the mass reach for the SSM Z' model in the resonance channels studied.

At first glance, this table shows the obvious correlation that higher center of mass collider energy reaches higher values in Z' mass, where the orders of magnitude spanned in collider energy pay off in orders of magnitude in Z' mass reach. This is justified since the resonance signal is assured when the Z' boson is within the kinematic reach of the collider. Moreover, for a given operating point of a collider, we see that the two Z' model benchmarks have very comparable results, which reflects the fact that the underlying charge assignments of SM fermions to the Z' currents only differ by $\mathcal{O}(1)$ factors, and so these results would be broadly applicable in other models where Z' bosons couple to all SM fermions, such as in gauged $B - L$

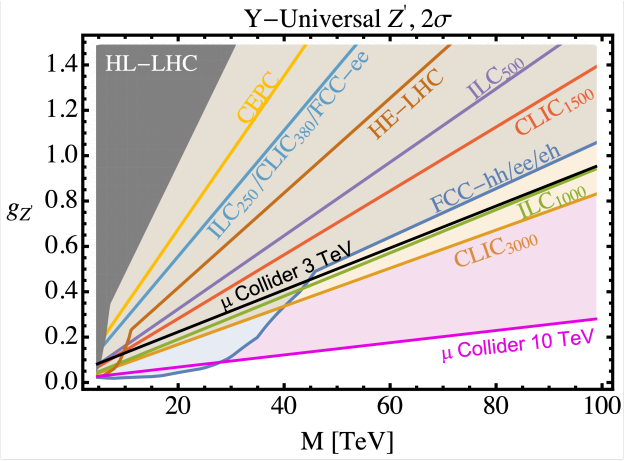


Figure 6-33. *Coupling versus mass reach at 95% CL for e^+e^- colliders (CEPC, ILC, CLIC and FCC-ee), pp colliders (HL-LHC, HE-LHC and FCC-hh), an electron-proton collider (FCC-eh) [411], and the Muon Collider [421].*

models. For more fermion-specific models, such as $L_\mu - L_\tau$ or gauged baryon number, which are equally relevant to the model benchmarks shown in Table 6-13, the distinction between the different colliders becomes dramatically more important since the Z' resonance would be produced via a tree-level coupling in some colliders while only produced via a kinetic mixing coupling or a loop-induced coupling in others. As a first estimate, the corresponding reach for a point of comparison to Table 6-13 would then adopt a coupling suppressed by a loop factor when the model does not couple to the initial partons at tree-level.

In Table 6-13 the relationship between the Z' mass reach at 95% CL and the mass reach at 5σ depends on the collider type and final state. The two sensitivities are roughly equal for dilepton final states at pp colliders, because the Z' peak is beyond the highest masses of the dilepton continuum background from electroweak production via Drell-Yan, a convincing and background-free exclusion or discovery. For dijet final states at pp colliders, the direct searches for a Z' dijet mass bump has a 95% CL mass reach that is roughly 20-30% larger than the 5σ mass reach, because here the continuum background is larger from strong production of dijets via QCD. Finally, lepton colliders search within the kinematic distributions of fermion pairs for the indirect effects of a Z', with huge backgrounds at di-fermion masses significantly lower than the Z' pole mass, resulting in a 95% CL mass reach that is roughly 60-100% larger than the 5σ mass reach. Therefore, Table 6-13 illustrates both the power of lepton colliders for indirect discovery of new physics, and the subsequent necessity of a higher energy to directly produce and confirm that new physics.

Searches for light but very weakly coupled new particles are motivated by a variety of new physics scenarios. A prime example is the ALP. While ALPs have a rich phenomenology, including prompt and long-lived signatures, one of the main phenomenological target at experiments is the ALP coupling to two photons, allowing a smooth transition between traditional QCD axion and ALP parameters. Figure 6-34 shows the results of Snowmass 2021 studies on the sensitivity to ALP, including the case of the Muon Collider [39, 429] compared with other colliders [36, 412] in the m_a vs. $g_{a\gamma\gamma}$ plane. For ALP decays to diphotons, a 10 TeV Muon Collider is the most sensitive to high ALP masses $m_a > 200$ GeV, from vector boson fusion production processes ($VV \to a \to \gamma\gamma$). FCC-ee has the best sensitivity in the medium mass range $1 \lesssim m_a < 100$ GeV, from the associated production process ($Z \to \gamma a$), thanks to the potentially very large integrated luminosity expected at the Z pole in circular e^+e^- colliders. In the more near term, the best collider limits on ALPs coupling to photons over the range $m_a \approx 0.1 - 100$ GeV will be set by exploiting photon-photon

Machine	Type	$\sqrt{s}$ (TeV)	$\int$ Ldt (ab^{-1})	Source	Z′ Model	5σ (TeV)	95% CL (TeV)
HL-LHC	pp	14	3	RH [424]	$Z'_{SSM} \to$ dijet	4.2	**5.2**
				ATLAS [425]	$Z'_{SSM} \to l^+l^-$	6.4	**6.5**
				CMS [426]	$Z'_{SSM} \to l^+l^-$	–	**6.8**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**6**
ILC250, CLIC380 or FCC-ee	e^+e^-	0.25	2	ILC [427]	$Z'_{SSM} \to f^+f^-$	4.9	**7.7**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**7**
HE-LHC	pp	27	15	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**11**
				ATLAS [425]	$Z'_{SSM} \to e^+e^-$	12.8	**12.8**
ILC	e^+e^-	0.5	4	ILC [427]	$Z'_{SSM} \to f^+f^-$	8.3	**13**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**13**
CLIC	e^+e^-	1.5	2.5	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**19**
Muon Collider	$\mu^+\mu^-$	3	1	IMCC [421]	$Z'_{Univ}(g_{Z'} = 0.2)$	10	**20**
ILC	e^+e^-	1	8	ILC [427]	$Z'_{SSM} \to f^+f^-$	14	**22**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**21**
CLIC	e^+e^-	3	5	EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**24**
FCC-hh	pp	100	30	RH [424]	$Z'_{SSM} \to$ dijet	25	**32**
				EPPSU [411]	$Z'_{Univ}(g_{Z'} = 0.2)$	–	**35**
				EPPSU [428]	$Z'_{SSM} \to l^+l^-$	43	**43**
Muon Collider	$\mu^+\mu^-$	10	10	IMCC [421]	$Z'_{Univ}(g_{Z'} = 0.2)$	42	**70**

Table 6-13. *List the operating point and mass reach, for 5σ discovery and 95% CL exclusion, of the SSM Z' model taken from Refs. [424–428], and the mass reach of the universal Z' model with a coupling $g_{Z'} = 0.2$ from Refs. [411, 421], determined from Fig. 6-33.*

collisions in ultraperipheral interactions of heavy-ions during the HL-LHC phase [384, 430]. It is worth noting that the ALP is typically expected to have non-suppressed coupling to gluons, in particular in its connection to the Strong CP puzzle of QCD [431, 432]. Having gluonic couplings changes the considerations for the search channels and the performance at different facilities appreciably (see recent phenomenological studies [158, 433, 434]).

The sensitivity to dijet resonances at pp colliders was explored during Snowmass 2021 as discussed in Refs. [36, 424, 435]. The process, $pp \to X \to 2$ jets, is an essential benchmark of discovery capability of pp colliders and is sensitive to a variety of models of new physics at the highest mass scales. The sensitivity to a dijet resonance is mainly determined by its cross section. The study considered strongly produced models, those with large production cross sections, that include scalar diquarks, colorons and excited quarks. At the highest resonance masses these strongly produced models can only be observed at a pp collider, as lepton colliders can only produce diquarks and excited quarks in pairs at significantly lower masses. Also considered are weakly produced models, with production cross sections that are roughly two orders of magnitude smaller, that include W's, Z's and Randall-Sundrum gravitons, which can also be observed at lepton colliders as previously discussed.

6.5.4 Long Lived Particles

Particles with long lifetime arise in many generic BSM models. The space of signatures for these long-lived particles (LLP) signatures is very rich and complicated, ranging from exotic-looking tracks to heavy

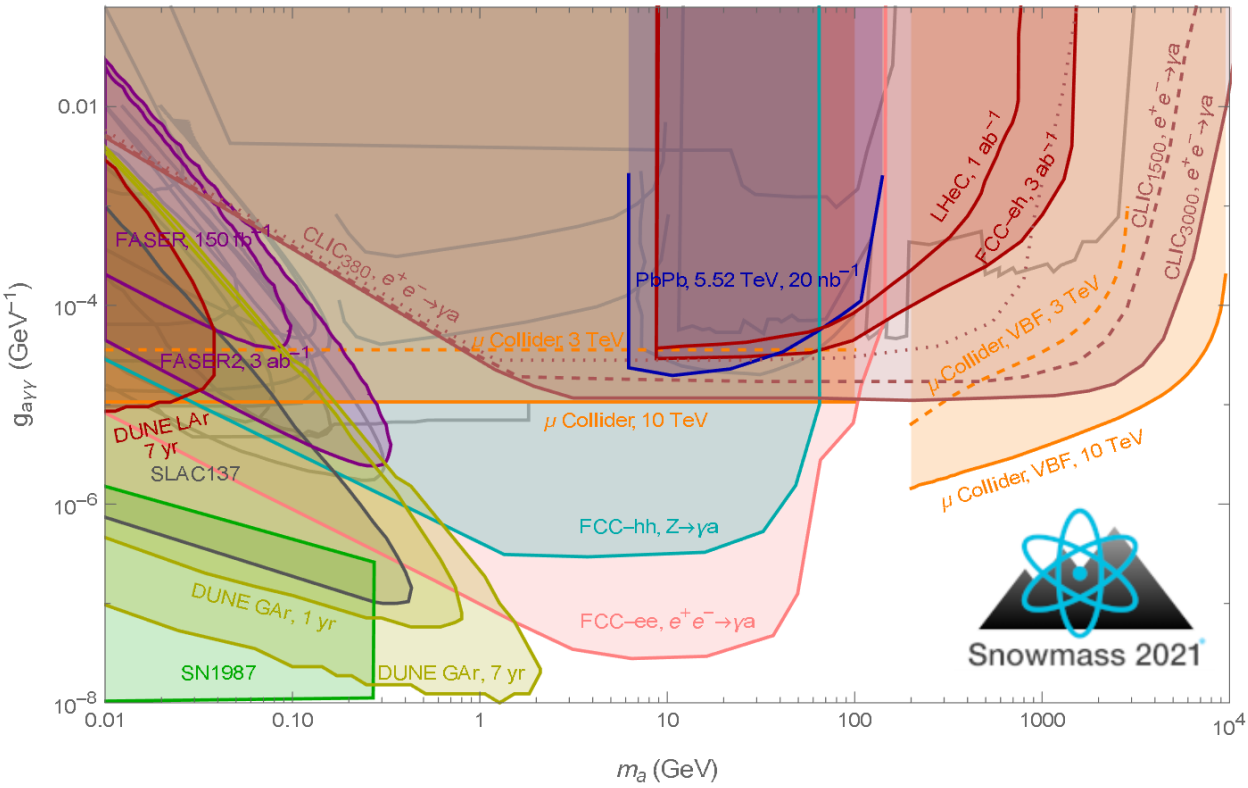


Figure 6-34. *The ALP coupling in the diphoton channel $g_{a\gamma\gamma}$ versus 95% CL mass reach is shown for multiple colliders [36, 412], including Snowmass 2021 studies on the Muon Collider [39, 429] (orange) at $\sqrt{s} = 3$ TeV (dashed) and 10 TeV (solid) as well as from the DUNE near detector [436] with liquid Argon technology (dark red) and gaseous Argon technology (dark yellow).*

stable charged particles to various types of displaced objects (e.g. vertices, jets, leptons). Here we highlight two examples. More benchmark cases, results, and discussions can be found in the BSM Topical Group report [18].

The first example is that of LLPs that are electrically charged and can be produced by many different models. In the case of one particular signature, if the charged LLP decays within the detector, the LLP could produce a disappearing track signature if it decays to neutral and/or very soft particles that cannot be reconstructed. Disappearing tracks are particularly motivated in models of SUSY and dark matter.

Figure 6-35 shows the projected reach of disappearing track signatures at the HL-LHC [30], HE-LHC [437], LE-FCC [411], FCC-ee [411], CEPC [411], CLIC [438], ILC [439], FCC-eh [153], FCC-hh [440], and several high energy Muon Colliders [441], assuming a pure Higgsino with its natural mass splitting. Further discussion on these constraints and their implications for dark-matter can be found in the section on dark matter. The sensitivities are driven by many factors, and in particular, the proximity of the tracking system to the interaction points and low pile-up environment could help enhance them.

Many new physics models with an hidden sector could lead to long-lived signatures and displaced vertices. Here we use a simplified heavy neutral lepton (HNL) model, motivated by the neutrino mass model building and the seesaw mechanism, as an example to show the different coverage of displaced signatures in the current and future experiments. For more details on different models and search coverage, see the discussion

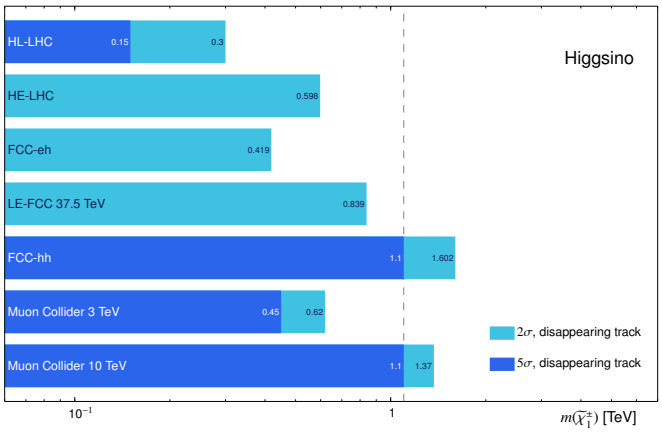


Figure 6-35. *Overview of the sensitivity to the pure Higgsino, assuming its natural mass splitting, for various future colliders. Figure adapted from Ref. [441].*

in the BSM Topical Group report [18]. Extensions to the SM that account for neutrinos masses typically incorporate heavy neutrinos that are "sterile" with very small mixings to SM neutrinos, and they have masses much larger than the eV scale. Neutral leptons with masses on the MeV scale or higher are referred to as *heavy* neutral leptons (HNLs).

In the timescale of HL-LHC and beyond, many proposed experiments could offer discovery potential for Type-1 Seesaw HNLs, particularly in the low-mass/small-coupling region where long-lived searches will be required. Figure 6-36, adapted from [463, 477], shows the expected reach of experiments such as FASER2, MATHUSLA, CODEXb, and future colliders. To guide the eye, the "type-I seesaw" line indicates the approximate parametric scaling associated with a simplified model with just a single neutrino flavor. Realistic three-generation models can populate the experimentally accessible regions in Fig. 6-36.

6.5.5 Dark Matter

The existence of dark matter (DM) is some of the most concrete evidence for particle physics beyond the Standard Model. However, little is known about DM beyond its gravitational effects. One of the central questions of particle and astroparticle physics is "*What is the nature of dark matter and how does it interact with ordinary matter?*".

Observing non-gravitational interactions of DM would bring us closer to answering this question. Many theoretical hypotheses foresee interactions between the DM and the SM to explain the measured relic dark matter density in the universe. Such DM-SM interactions are also key to terrestrial searches for dark matter. Since DM-SM interactions are generally feeble (as a consequence of DM's *darkness*), DM produced in SM-particle collisions would escape detection at collider experiments. Nevertheless, these invisible particles can be discovered when collisions appear to fail to conserve transverse momentum, leading to missing transverse momentum in a hermetic detector.

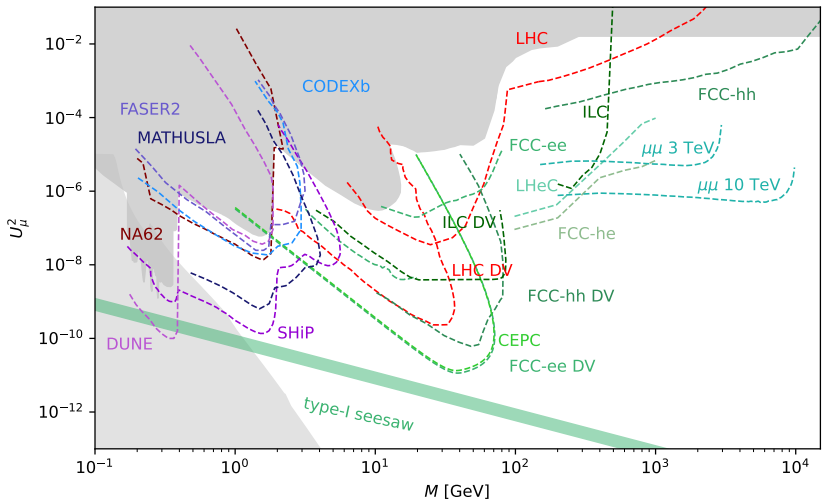


Figure 6-36. *Constraints and future sensitivities for HNLs with mass M and mixing U_μ^2 with muon neutrinos (summed over three HNL flavours).* Medium gray: *Constraints on the mixing of HNLs from past experiments [442–452].* Colourful lines: *Estimated sensitivities of the main HL-LHC detectors [453–455]) and NA62 [456], with the sensitivities of selected planned or proposed experiments [457–462], as well proposed future colliders [463–472].* Green band: *Indicative lower bound on the total HNL mixing $U_e^2 + U_\mu^2 + U_\tau^2$ from the requirement to explain the light neutrino oscillation data [473] when varying the lightest neutrino mass and marginalising over light neutrino mass orderings.* Light gray: *Lower bound on U_μ^2 from BBN [474, 475].* *More details can be found in Refs. [18, 476]*

While finding the connection between new invisible particles at colliders and astrophysical DM requires an observation of DM in astrophysics experiments[3], to verify the new particle's cosmological connection, collider experiments have unique abilities to study DM-SM interactions and the properties of DM in detail, including discovering new high energy particles that mediate the interactions. The historical discovery of other invisible particles – neutrinos – offers an example of such synergy: an observation of neutron decays at low energies required high energy colliders for the study of neutrino interactions and the discovery and study of the weak force mediators.

Following this example, here we focus on DM search benchmarks where the SM-DM interaction is mediated by either an existing or a new particle, which in turn decays into invisible (DM) particles and can also decay back into SM particles allowing for a discovery in visible final states. Collider experiments can also investigate theories of complex dark sectors and the wealth of particles they hypothesize.

6.5.5.1 Testing the traditional WIMP paradigm

Among the possible theories of particle DM, WIMPs have been the most prominent target of experiments. These are also theories to which colliders are especially well-suited. In the traditional WIMP scenario, DM consists of a single particle of mass between roughly 1 GeV and 100 TeV. As a thermal relic, its mass and coupling to the SM allow them to reach a common thermal equilibrium in the early universe and

[3]The search for dark matter must be conducted in synergy between different Frontiers, using multiple probes and assumptions. This is discussed in the Snowmass 2021 cross-frontier report on DM complementarity [478].

control the present abundance of dark matter, largely independent of the universe's initial conditions and evolutionary history. WIMP candidates feature in many theories with connections to other EW-scale new physics, including supersymmetry, the archetype for the WIMP idea [479].

Since the 2013 Snowmass report, experiments at LHC Run 2, as well as at underground facilities and with astrophysical observations, have made significant progress in ruling out some possible WIMP parameters. Nevertheless, others remain a compelling target for DM searches at colliders and beyond (see, among numerous others, Refs. [480–486], for example).

Broadly speaking, WIMPs can be classified according to the way in which the DM particle coupled with the Standard Model. Here we discuss some of the most widely-studied model categories.

Minimal WIMPs. One simple, predictive WIMP scenario identifies the DM particle as the lightest member of an EW multiplet. Examples are the Higgsino (a Dirac fermion doublet) and the Wino (a Majorana fermion triplet) in supersymmetry. More general cases have also been considered [487,488]. In these models, the interaction strengths are fixed by the SM gauging couplings, and the only free parameter, the mass of the dark matter particle, m_χ, is chosen to give the observed thermal relic abundance [489]. These "thermal" targets are typically in the TeV range [490–495] and it is critical to probe them at future high-energy colliders.

Figure 6-37 summarizes projections for 2σ exclusions from future colliders for Higgsino and Wino DM. New studies of the reach of a high energy Muon Collider [441, 485, 496–500] were developed within Snowmass 2021 in addition to the studies within the Briefing Book for the European Strategy for Particle Physics Update [412].

At hadron colliders, the dominant signature of WIMP DM is often (but not always) large missing transverse momentum recoiling against SM particles (e.g. jets) [437,501]. At lepton colliders, other signatures involving SM EW gauge bosons and leptons come into play [485, 496, 497, 499, 500]. These signals are relatively insensitive to the splitting between masses of the EW multiplet and, hence, more robust against variations beyond the minimal scenario. The loop-induced mass splitting among the components of the EW multiplet also results in a disappearing track signature which can enhance the reach but is more sensitive to the mass splitting and detector backgrounds.

The basic lesson from Fig. 6-37 is that high energy colliders, such as a hadron collider with $E_{\rm CM} \simeq 100$ TeV or a Muon Collider with $E_{\rm CM} \simeq 10$ TeV, can definitively test these scenarios. High energy e^+e^- colliders, with energies up to 3 TeV, can cover lower-mass regions.

Higgs mediation. DM could also couple to the SM via *portals*, which is a direct coupling via gauge-invariant operators. The Higgs boson provides a prime example: as a spin-0 particle, this 'Higgs portal' allows a renormalizable coupling with the DM that can have a sizable effects on SM Higgs properties. Searches at colliders are powerful probes of the Higgs portal. For example, DM production would enhance tiny rate of invisible decays of the Higgs predicted by the SM, provided the DM mass is less than half the Higgs mass. Precision measurements of the Higgs couplings, another main objectives of a future collider, would also contribute to probe the Higgs portal scenario. Future prospects for the Higgs portal were studied in the European Strategy physics Briefing Book [412] and are discussed in the BSM Topical Group report [18].

Models involving a larger extension of the scalar sector can also be probed with Higgs measurements and BSM Higgs searches. Example of such extensions are the Inert Doublet Model, where an extra scalar doublet provides a DM candidate, and a 2HDM where an additional pseudoscalar has direct couplings to DM. The HL-LHC and lepton colliders are expected to be sensitive to large parts of the parameter space of these models, as can be seen in studies targeting specific signatures [30,503,504].

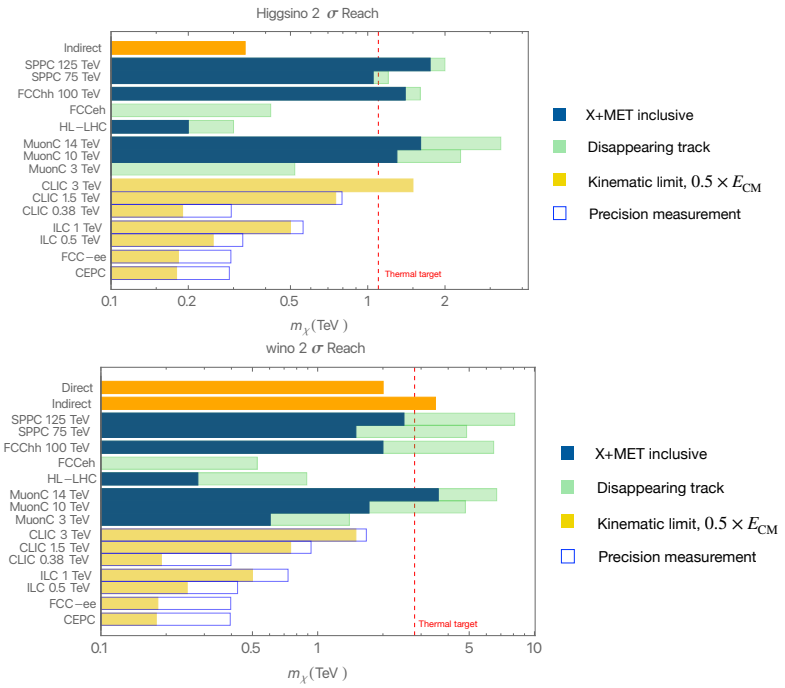


Figure 6-37. *A summary of the reach of future colliders for simple WIMPs from four search strategies, as indicated in the legend. For comparison, the reaches of the direct and indirection detectors are also included (orange bars at top). For lepton colliders where a detailed study is not available, the kinematic limit $m_\chi = 0.5 \times E_{CM}$ is used to indicate potential reach; Muon-collider studies suggest this is likely to be an overestimate. Hadron-collider projections are from [440, 502], while lepton-collider projections are from projections in [441, 496, 497].*

BSM mediation. Another category of models involves DM interacting with the SM only via one or more new bosons. Although this category encompasses a huge set of possible models, it is likely that only a few new particles will be relevant in the early phase of a discovery. The relevant phenomenology can be captured by simplified models of collider DM production.

The simplified models used to design present LHC searches, described in Ref. [505], are inspired by the vector and scalar bosons of the SM. They involve a single fermionic DM species and a mediator particle, either a vector (Z') with pure vector or axial-vector couplings to SM and DM fermions, or a scalar or pseudoscalar boson with Yukawa couplings to the SM and DM fermions. This involves 4 to 6 free parameters such as the masses of the DM and the mediator, and their couplings to the SM and DM.

Contributions to Snowmass 2021 have significantly extended the projections made for these models by the recent European Strategy Update Briefing Book [412]. Prior results, originally focusing on relatively large coupling values appropriate for LHC Run 2 [506, 507], have now been extended to arbitrary coupling values [508]. This provides a better picture of how future experiments would improve upon current searches and complement direct-detection and indirect-detection experiments, especially when the dark matter mass is less than a few GeV. The new studies of coupling dependence are especially useful in understanding the effect of different coupling values assumed for the signal at colliders [509], while direct detection only depends on a specific combination of the couplings and the mass of the mediator.

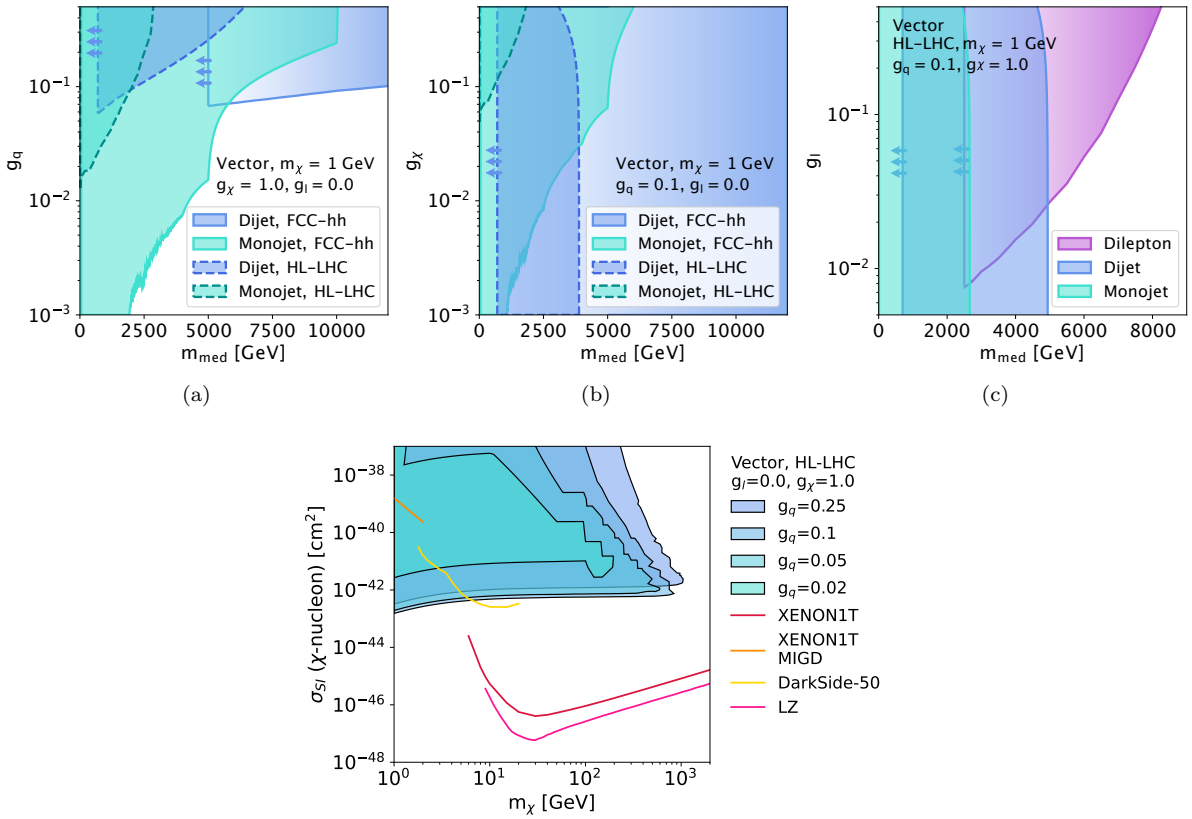


Figure 6-38. ***Top**: Projected exclusion limits on the couplings g_q (a), g_χ (b), and g_l (c) for a vector mediator at the HL-LHC and FCC-hh (for quark and DM couplings only). The result is shown as a function of the mediator mass m_{med}; the mass of the DM candidate is fixed to 1 GeV in all cases. The coupling on the y axis is varied while the other two couplings are fixed: in (a), g_χ=1.0 and g_l=0.0; in (b), g_q=0.1 and g_l=0.0; and in (c), g_q=0.25 and g_χ=1.0. The arrows in the lower edge of the contours indicate that other searches for lower mass mediators that are normally performed at colliders could be sensitive to these models, but are not shown because the inputs received focused on the highest mediator masses only. It is worth noting that the lower bounds for both HL-LHC and FCC-hh for mediator (resonance) searches shown in the figure can be significantly improved by using non-standard data taking techniques such as data scouting/trigger-level analysis described in Section 6.A.1 and in Refs. [510, 511] specifically for dijet resonances. **Bottom**: Example of the effects on the HL-LHC exclusion limits in $\sigma_{\rm SI}$ for the monojet search (d) when varying the quark coupling, g_q. The dark matter coupling is held fixed to $g_{\rm DM} = 1$ and there is no coupling to leptons. Limits from existing direct detection experiments [105, 113, 115, 513] are shown for context (a recent re-analysis of the DarkSide-50 data [516] has subsequently become available).*

The top panels of Fig. 6-38 show the projections for future hadron colliders for couplings to the SM fermions and DM fermion. These are derived from the projections for missing-momentum signatures of the mediator (e.g. jet plus missing transverse momentum, or *mono-jet*) as well as searches for the visible decays (e.g. dijet and dilepton resonances). Observing both visible and invisible mediator decays would provide complementary views of DM-SM interactions. Hadron colliders with a higher center-of-mass energy can reach higher mediator and dark matter masses. Searches for invisible particles should be able to constrain models with much smaller couplings than current searches, especially at mediator masses below the TeV. These results can also be

recast in terms of dark-photon benchmark models used by the Rare Processes and Precision Measurements Frontier [9], as discussed in the next Section.

The reach of future colliders for these simplified models is dependent on the interaction strength between the mediator and the SM, especially the quark coupling of the mediator, which governs its production. It is expected that lepton colliders will also strongly constrain models with lepton couplings, especially in the case of polarized beams [517].

In order to understand when direct and indirect detection experiments can confirm that collider signals are connected to DM, the European Strategy Briefing Book compared collider and direct/indirect detection experiments, highlighting where a simultaneous discovery would be possible.

Following those studies, the searches shown in the top row panels of Fig. 6-38 can be reparameterized as limits on the DM-nucleon cross section for direct detection searches, as shown in Fig. 6-38(b). As expected from Refs. [506, 507], as future collider searches reach smaller SM-DM and SM-SM couplings, their coverage in the DM-nucleon cross section plane improves. When the coupling sensitivity limit approaches, collider projections gradually disappear.

The sensitivity of collider searches also depends on the ratio of the DM to mediator mass. Searches at colliders are most sensitive when the mediator can be produced directly from SM particle collision, and when the mediator is much heavier than the DM particle. However, a strength of collider experiments is that constraints on the dark interactions for these models can also be obtained when the DM is too heavy to be produced directly. In BSM mediation (as well as EFT) models, different mass hierarchy hypotheses are plausible, so different mass ratios as well as different couplings should be tested. We refer to the following section for a specific choice of a benchmark for a vector mediator, motivated by thermal relic DM.

The lessons from these plots remain similar to Ref. [412]. When particle DM is discovered in a direct- or indirect-detection search, Fig. 6-38(b) illustrate – in a necessarily model-dependent fashion for the specific simplified model considered – when collider searches for invisible particles would also be sensitive to production of the mediator. In roughly these regions, both types of searches would have complementary discovery potential, as discovery at a direct-detection experiment would be combined with further study of the type and properties of the DM-SM interaction at a hadron collider.

These figures also indicate where collider searches for invisible particles would add unique sensitivity to the coverage from the other DM experiments. Nevertheless, even in these regions, other experiments would be essential to confirm that the invisible particles are indeed associated with galactic dark matter.

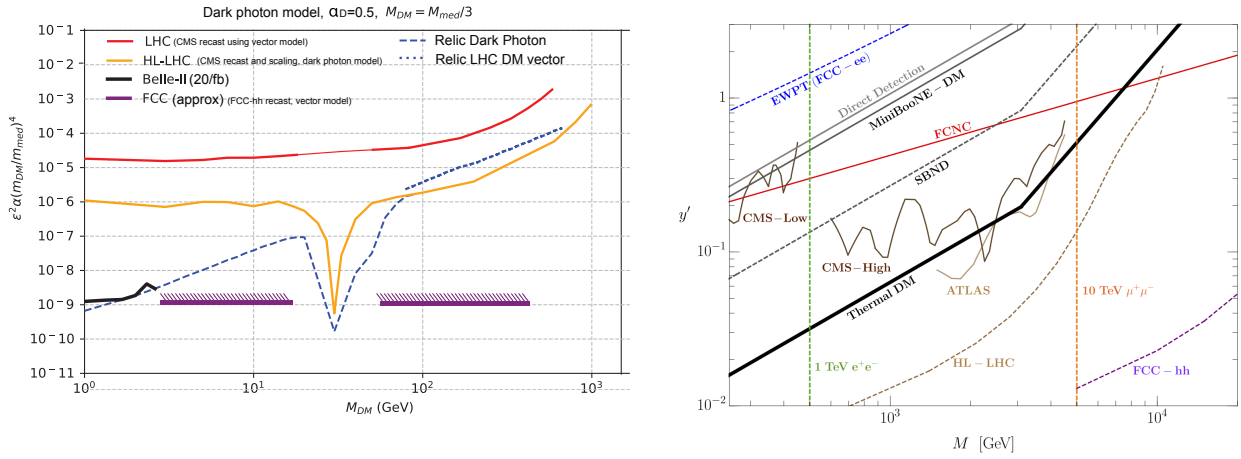
6.5.5.2 Beyond WIMP dark matter

As the astrophysical evidence for dark matter does not point to a particular mass scale for DM particles, there are many other intriguing DM hypotheses beyond the WIMP that can be probed at colliders and neighboring facilities. These viable possibilities include extending the thermal relic paradigm to lighter DM (below 1 GeV), provided it has feeble couplings to SM, or more complex dark sectors signatures that can also include long-lived particles. Here, we will highlight some representative beyond-WIMP DM models and the prospects for their discovery at future colliders and complementary facilities.

Portal models for DM: dark photon and dark Higgs. The experimental characteristics of feebly-coupled, low-mass thermal relic DM particles can be represented by a small set of relevant interactions, mediated by new *portal* particles, akin to the simplified models mentioned above. One such portal particle is a new, low-mass vector boson, commonly called *dark photon*, that couples to DM and to the SM via a

new electromagnetic-like interaction (kinetic mixing). A dark photon benchmark model has been adopted by the Rare Processes and Precision Measurements Frontier [9] to compare the sensitivity of accelerator experiments to thermal DM below a GeV. Colliders can also probe such a dark photon in a complementary way.

The left panel of Fig. 6-39 reinterprets present and future collider searches for vector-mediated DM in terms of the parameters of this dark-photon benchmark, for a pseudo-Dirac DM particle with a mass below a TeV. It shows that the HL-LHC dataset is needed to reach the thermal relic milestone for DM masses above roughly 100 GeV, while FCC-hh is needed to cover the remaining parameter space[4]. High-energy collider experiments are therefore needed, together with accelerator and B-factory experiments, to explore the full mass range for DM in this scenario.



(a) (b)

Figure 6-39. *(a) Comparison of the expected constraints for the dark photon model, starting from the reinterpretation of the results [518] in terms of the simplified vector mediator model (LHC), and for HL-LHC, FCC-hh and Belle-II 20/fb [43, 71] in terms of the dark photon model and (b) existing constraints and future prospects for the up-specific scalar mediator S in the renormalizable completion described in [521, 522]. Each figure also depicts the parameter combinations that would reproduce a thermal relic.*

Although not immediately obvious from the formulation of minimal benchmarks [521–523], many portal models require both low and high mass particles to be self-consistent. New TeV-scale particles at loop-level are needed to generate the kinetic mixing interaction that characterizes dark-photon models. These particles present discovery opportunities at colliders such as HL-LHC or the FCC complex, and could be inferred from precision measurements at lepton colliders [523]. For instance, if a light scalar singlet (a dark Higgs) decaying to light DM couples predominantly to one SM fermion family, then new heavy states are required to keep the model self-consistent at higher energy scales [51, 521, 522, 524]. In this example, the Higgs-boson mass and the DM mass are both of the order of a GeV, while the other particles needed to complete the model have masses of the order of a TeV. Figure 6-39(b) shows estimates for current and future collider searches for these new particles.

Similar considerations are generically applicable to different types of portal models, encouraging complementary probes for the lower-energy phenomenology of this model and higher-energy particles required for the

[4] This model assumes that the DM particle constitutes the entire astrophysical DM abundance. For the thermal relic in all such simple models, this is not a strict requirement if other processes not present in minimal model enhance or deplete the DM abundance.

completion. Light portal particles (e.g. light dark Higgs, dark photon) with feeble couplings can be discovered at Rare and Precision Frontier experiments [9], while the higher-energy particles can be discovered at future hadron or Muon Colliders. A corresponding discovery in low-threshold Cosmic Frontier experiments [10] would determine the cosmological nature of the dark matter particle.

More complex dark sectors. Taken further, dark sectors could reach or exceed the complexity of the Standard Model, for example in the class of *Hidden Valley* models [525] where a portal particle feebly couples ordinary matter to a more complex dark spectrum. Dark sector models can include a large number of states with different masses and lifetimes, where a viable DM candidate arises from the uncharged states of the dark sector [526–529]. These lead to qualitatively different signals with respect to WIMP dark matter.

Alternate mechanisms to obtain the DM abundance as well as new forces can point to new dark matter candidates and parameter regions. In particular, new QCD-like confining forces within the dark sector (a 'dark QCD' [530]) can give rise to stable dark hadrons that can be viable DM candidates. These dark hadrons can be embedded in *dark showers* that could be discovered at present and future colliders [531]. A dark-sector–confining phase transition can also lead to new viable masses for dark matter [532]. As for the other models, connecting collider signals to cosmology requires other experiments[5].

As these models offer myriad ways to connect colliders to cosmology via the dynamics of a complicated dark sector, future efforts to explore such a connection are needed to identify regions of parameter space that are cosmologically interesting, and to help contextualise future discoveries in multiple Frontiers.

Dark sector discoveries at facilities co-located with EF colliders: the FPF example. The signatures generated by feebly-coupled models often include particles with long lifetimes, as discussed earlier. Covering these signatures at colliders requires both general-purpose and highly-optimized experiments. In particular, portal models and beyond-WIMP models are targets for dedicated facilities and experiments designed to use existing high-energy beams and supplemented by information recorded at traditional collider experiments. Collisions of high energy beams produce a large, forward flux of secondary particles, including light DM of dark-sector particles, that are best investigated by dedicated experiments in facilities downstream from the standard detectors.

An example of such a facility is the FPF, proposed to be installed in the long shutdown between the LHC Run 3 and the start of the HL-LHC [138, 158]. In particular, the proposed FLArE [534] experiment would be sensitive to thermal-relic DM mediated by a dark photon, and experiments such as FASER2 [458] and FORMOSA [535] would target a number of DM and dark-sector scenarios. The opportunities for DM discoveries (as well as of neutrino measurements relevant to cosmic DM experiments) offered by the FPF would further enhance the HL-LHC DM and dark-sector search program, especially since development and construction can be performed in parallel.

Future colliders offer opportunities for similar compelling experiments for DM physics. Smaller-scale experiments can be optimized to cover a number of beyond-WIMP scenarios that complement and enhance what can be discovered at the larger, general-purpose experiments, while exploiting the same colliding beams.

6.5.5.3 Dark matter complementarity

The search for DM has become a major science driver across all experimental frontiers (CF, EF, RF and NF) and the cross-cutting AF, IF, UF and TF frontiers. Discovering its microscopic physics requires

[5] Additional information on the dark sector spectrum can come from the lattice community, see e.g. [533]

collaboration within and across all of these communities, and a variety of experiments at different scales. The first step toward a unified strategy, understanding how the efforts of each community complement the others, is discussed in a separate community whitepaper, the Snowmass 2021 Dark Matter Complementarity report [478]. This document, developed by the combined effort of these communities, sketches opportunities for cooperation, lays out a road map for a coherent strategy and presents case studies for discovery.

6.6 The Energy Frontier vision

The EF community has proposed several opportunities for pursuing its scientific goals, among them the most prominent ones are Higgs-boson factories and multi-TeV colliders at the Energy Frontier. These projects have the potential to be truly transformative as they will push the boundaries of our knowledge by testing the limits of the SM and directly discovering new physics beyond the SM. [6]

The EF aims to facilitate US leadership in an innovative, comprehensive, and international program of collider physics. The timescales to fully realize the EF vision extend to the end of this century, and the ultimate goals can only be realized if our actions foster a vibrant, diverse, and intellectually rich US EF community. Maintaining and strengthening such a community is only possible if our plans reflect the aspirations of and provide a rich set of opportunities for Early Career physicists.

During the coming decade it is essential to complete the highest priority recommendation of the last community planning exercise (P5) and to fully realize the scientific potential of the HL-LHC by collecting and analyzing at least 3 ab^{-1} of integrated luminosity. The precision electroweak measurements possible at an e^+e^- collider (Higgs factory) would greatly extend and complement the scientific results provided by the HL-LHC. The EF endorses making the investments now to enable US leadership in a Higgs factory and start the construction for a Higgs factory in parallel with HL-LHC operations. To realize this goal, the US EF community needs to expand the R&D, in collaboration with the international community on the detector and accelerator technologies which will be required for a Higgs factory. In addition, the global HEP community should consider opening a dialogue for a US-based site for a future e^+e^- collider.

The next step in our exploration of the fundamental properties of matter requires the exploration of the multi-TeV energy scale. Any deviations observed at HL-LHC or an e^+e^- Higgs factory would strongly motivate such a program. Two possible and potentially complementary paths forward appear most promising to develop the capability to explore the energy-scale frontier: 1) a 100 TeV (or higher) hadron collider, and 2) a high-energy Muon Collider. The community proposes the US (in collaboration with international partners) embark on a R&D program addressing high-priority critical aspects of accelerators to reach these high energies, and to develop the detector technologies needed to withstand the complex backgrounds and high radiation environments envisioned for these two types of future colliders.

Thus, the energy frontier believes that it is essential to complete the HL-LHC program, to support construction of a Higgs factory, and to ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a Muon Collider or a hadron collider.

A key role in the success of the US EF at the HL-LHC, at future e^+e^- colliders (Higgs factories) as well as at future multi-TeV colliders is played by the Theory Frontier: model building, precision calculations and

[6] The EF vision, as outlined in the following, has been formulated from the input received directly from the Energy Frontier community during the Snowmass process, including EF wide meetings and workshops, Topical Group meetings, and Agorá events on future colliders. Full documentation of these activities can be found on the Snowmass 2021 EF wiki page [536].

simulations are necessary for precision measurements and searches of new physics. The theory community must be adequately funded to support the success of the EF community as a whole. In addition, the EF community thrives on collaborating with other frontiers within HEP, and has relied on cross-fertilization opportunities available via the interdependence with various fields and opportunities, see Sec. 6.A.2.

It is essential for the US and the global HEP community to develop an integrated plan for future colliders to pursue the reach of our ultimate goal of uncovering new particles, new forces, and unveiling more fundamental laws of nature.

6.6.1 The immediate-future Energy Frontier collider

The immediate future is the HL-LHC. The physics case for this program rests on its ability (1) to extend the direct search for new elementary particles, (2) to measure the couplings of the Higgs boson at a level that is sensitive to corrections from physics beyond the SM, (3) to demonstrate the presence of a self-coupling of the Higgs boson, (4) to measure the couplings of the top quark at a level that is sensitive to corrections from physics beyond the SM, and (5) to extend our understanding of QCD and strong interactions by improving the precision of the corresponding relevant measurements.

The results from the HL-LHC set the basis for any vision of the future of the EF program. The EF scientific program at the LHC is thriving and Run 3 will triple the current integrated luminosity. The HL-LHC is scheduled to start operation in 2029 and to increase the integrated luminosity by another factor of 5 over the following decade. The HL-LHC program spans a very wide range of physics topics, where some legacy results are expected to remain the most sensitive for a long period of time after the end of the HL-LHC data-taking. The unprecedented data set accumulated at the HL-LHC will allow the study of SM phenomena that remain elusive so far because of their small rates, and to extend the reach of searches for new processes beyond the SM. These data will boost the potential of the experiments to make direct discoveries which may revolutionize the human understanding of nature. These results rely both on innovative detector technology, and a major theoretical undertaking in reducing the expected systematics.

The study of the Higgs-boson self-interaction is one of the primary goals of the HL-LHC due to its role in cosmological theories, involving, for example, the vacuum stability. Higgs-boson pair production is a flagship measurement, with a projected evidence of a di-Higgs signature at the 4σ level, by the end of HL-LHC running. Among all the Higgs-boson self-interaction terms, the trilinear self-interaction is the only one in the reach of the HL-LHC and it is parametrized by the coupling strength, which can be measured with a sensitivity of 50%.

Studying the properties of the Higgs boson is a key mission of the HL-LHC. Uncertainties in the signal strength modifier and coupling measurements in the main production and decay channels will reduce from their current levels of 10-50% to less than 5%, moving Higgs-boson measurements into the regime of precision physics, and allowing for spotting deviations from the SM. Rare processes such as Higgs-boson decays to $c\bar{c}$, which are challenging, and currently at the level of about 7.6 times the SM cross section, will become accessible at the HL-LHC. The sensitivity to the H $\rightarrow$ invisible branching ratio would reduce from the current $\sim$20% to a few percent, approaching the SM prediction of 0.1%. For the heavy Higgs bosons predicted by BSM theories with extended scalar sectors, the reach would increase to masses up to 1 TeV.

The HL-LHC will also extend the sensitivity in direct searches for BSM particles. For example, in SUSY, the reach for gluinos and squarks will increase by up to 1-2 TeV, while chargino, neutralino and slepton reach will increase by up to 0.5-1 TeV. This will allow to make a more conclusive statement on the naturalness hypothesis. The reach for new resonances decaying to SM particles will extend on average by 2-3 TeV.

Moreoever, HL-LHC will provide the ability of studying resonance decays to lighter BSM particles, such as in the case of Z' decays to charginos, which are barely accessible at the LHC, due to typically small branching ratios. Another set of dedicated searches will look for dark matter, typically in final states with invisible dark matter and visible mono-X and increase the current sensitivity. Sensitivity to long-lived particles will be especially enhanced at the HL-LHC due to improved and innovative detectors. The reach for Higgsinos via a disappearing track search will increase to masses up to 350 GeV. Sensitivity to long lived neutralinos decaying to photon and graviton is expected to increase to masses of 700 GeV, improving the reach in short $c\tau$ and at high masses. Additionaly, dedicated displaced muon reconstruction will improve cross section reach for smuons or dark photons by 1-2 orders of magnitude for different values of lifetime with respect to Run 3.

Expected measurements of QCD interactions, e.g. in jet, photon as well as in W and Z boson productions, will considerably improve the understanding of PDFs at low and high momentum fraction x, which are critical for carrying out the rich physics program of precision Higgs-boson measurements as well as BSM searches. Heavy Ion studies at the HL-LHC will include measurements of parton densities in broad kinematic range and search for saturation, precision measurement of macroscopic long wavelength QGP properties, developing a unified picture of collectivity across colliding systems, assessing microscopic parton dynamics underlying QGP properties, and performing precision QED and BSM physics, for example in ultraperipheral collisions.

The international collaborations at the LHC recognize the importance of the Snowmass 2021 process to the HEP community in the US and beyond. Continued strong US participation is in particular critical and essential to the success of the HL-LHC physics program, including the Phase-2 detector upgrades, the HL-LHC data-taking operations, and the physics analyses based on the HL-LHC dataset.

Additionally, auxiliary experiments and facilities are proposed to take advantage in far forward kinematic regions. Forward physics facilities allow to further extend the breadth of the HL-LHC physics: they can study regions of parameter phase space for BSM, for example in LLPs and DM searches, that would otherwise remain uncovered, and can perform novel QCD and neutrino measurements in the very forward region.

We note that cross domain collaboration and studies with the EIC measurements (under the purview of the DOE nuclear physics) identified the synergies and complementarities in many physics studies, experimental technologies, analysis techniques, and theoretical tools.

The US HEP community is heavily involved in ATLAS, CMS, LHCb, and ALICE, and it contributes to aspects of the LHC accelerator infrastructure. More than half of the US HEP community is involved in the LHC. Over the last years, US institutions have graduated about 100 PhDs/year based on research carried out with LHC data. During the last decade, ATLAS and CMS have together published more than 2000 scientific papers in peer reviewed journals. This has had a significant impact on the advancement of the field, and is an unprecedented achievement compared to any previous collider experiment. In addition, the PhDs apply the valuable skills they learn during their research to many domains of science and industry, which is an essential positive economic return of the LHC program. The vibrant scientific program of the HL-LHC will continue this tradition and provide excellent training environment to the next generation of students and postdoctoral researchers. Given the broad portfolio of HL-LHC, similar number of student cohorts, i.e. about 100 PhDs/year from the US are expected to benefit from the HL-LHC program.

In conclusion, our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

At the same time, the time scales for realizing what comes next require also an effort to advance preparations for the next collider of the intermediate future during this time frame. This is reflected in the discussion on needs and timelines in Sec. 6.

6.6.2 The intermediate-future Energy Frontier collider

The intermediate future is the an e^+e^- Higgs factory, either based on a linear or a circular collider. The physics case for this program rest on its ability to (1) measure the couplings of the Higgs boson to the sub-percent level and discern the pattern of modifications from beyond the Standard Model, (2) search for exotic Higgs decays due to a "Higgs portal" to a hidden sector of forces, (3) measure the parameters of the Standard Model, including the Z, W, top, and Higgs-boson masses to very high precision, and to provide stringent tests of couplings in the electroweak sector, (4) measure the electroweak couplings of the top quark at a level that can clearly reveal corrections from beyond the Standard Model, and (5) perform precision measurements of QCD phenomena which are testing-grounds of QFT in both perturbative and non-perturbative regimes, and provide complementary information relevant to cosmology and BSM physics.

The e^+e^- colliders are the vehicle that will enable a high-precision physics program in the EW sector by increasing the precision of SM measurements. The physics case for an e^+e^- Higgs factory is compelling and the program is possible essentially with current technology. The various proposed facilities have a strong core of common physics goals that underscores the importance of realizing at least one such collider somewhere in the world. A timely implementation of a Higgs factory is important, as there is considerable US support for initiatives that can be achieved on a time scale relevant for early career physicists.

Circular e^+e^- colliders will be implemented in stages as electroweak, flavor, QCD, Higgs-boson, and top-quark factories by spanning the energy range from the Z pole (and below) up to the top-quark pair threshold and beyond. The highlights of such colliders are the highest luminosities at the Z pole, WW threshold, and Zh energies (the "intensity frontier"); the exquisite beam energy calibration at the Z pole and WW threshold; the possibility of center-of-mass energy monochromatization at $\sqrt{s} = m_h$; the compatibility with four interaction points; and the cleanest experimental environment. Circular e^+e^- colliders are therefore excellent Higgs factories: they produce over a million Higgs bosons in three years at 240 GeV center-of-mass energy. They provide the most precise determination of the Higgs-boson coupling to the Z boson, and of the Higgs-boson width (and mass), and they could provide the opportunity for the discovery of the Higgs-boson self-coupling and for a first measurement of the electron Yukawa coupling. These colliders are also much more than Higgs factories. At the Z pole, the Tera-Z factory, with several trillions Z produced, offers opportunities for a comprehensive set of electroweak measurements with the best prospects for precision, such as Z-boson mass and width (10's of keV), effective weak mixing angle (few 10^{-6}), a direct determination of the electromagnetic coupling constant, which allow sensitivity to mass scales up to 70 TeV to be reached. In addition, a Tera-Z factory has comprehensive programs for QCD physics, e.g. the most precise measurement of the strong coupling constant, flavor and rare decay physics, e.g. the search for lepton-flavor violation, as well as direct searches for heavy neutral leptons, axion-like particles, and other feebly coupled dark matter particle candidates. Collisions at the WW threshold will allow the most precise determination of the W mass (300 keV) and width (1 MeV), while running at the top-pair threshold, will provide the best prospect for the top mass measurement.

Linear e^+e^- colliders are primarily aimed at precision measurement of the Higgs-boson properties with the aim to potentially flag violations of the SM. The linear e^+e^- colliders will also run at center-of-mass energies covering the production thresholds of the Z boson, WW pairs, Zh pairs, $t\bar{t}$ pairs, and tH and Higgs-boson

pair production. The center-of-mass energy can be chosen flexibly depending on new discoveries at the LHC, or elsewhere. The e^+e^- linear collider will use polarized electron and positron beams to enhance signal reactions and allow the measurement of helicity-dependent observables, multiplying the physics output per unit of luminosity. Beam polarization also enables the suppression of backgrounds and provides cross-checks for the control of systematic errors. In electroweak measurements, beam polarization gives direct access to Z left-right asymmetries, which are very sensitive precision probes. For example, in a dedicated run at the Z pole, it allows a measurement of $\sin^2\theta_w$ at the level of 10^{-5}, comparable to the TeraZ capability. The nominal e^+e^- collider physics program begins with running at a center of mass energy of 250 GeV. At this energy the total cross section and the branching ratios for all Higgs decays can be determined, including decays to invisible final states. It provides the potential to search for exotic Higgs decays. These measurements will improve our knowledge of Higgs-boson couplings by a large margin over HL-LHC results. A global fit using an EFT framework allows for a determination of the hbb couplings to 1%, the hWW and hZZ to 0.7%, and all other important Higgs boson couplings to close to 1%. These levels of precision are sufficient to be sensitive to new physics beyond the reach of direct searches at the LHC. The second step in the linear e^+e^- collider program would be an energy upgrade to ∼600 GeV. This would improve the precision of all measurements from the 250 GeV running by a factor two. Beyond the improved precision of the Higgs-boson couplings, the couplings of the top quark can be explored and it is possible to search for pair production of new particles produced in EW interactions that are difficult to discover at LHC. At $\sqrt{s}$ of 500 GeV, the Higgs pair production can be observed and the Higgs-boson trilinear coupling can be measured with a precision of 22%.

As the physics case for a Higgs factory is strong, the US should participate in global efforts to construct an e^+e^- collider. Planning the center-of-mass energy of this collider is important, and planned upgrades of the center-of-mass energy will provide access to a broader spectrum of Standard Model physics, including top-quark physics, which is an important component of the energy frontier physics program. The accelerator R&D should aim at developing sustainable facilities for Higgs research at a reasonable cost. To enable the realization of a Higgs factory in the shortest possible timescale, a targeted program on detector R&D for Higgs factories should be supported with an immediate start and with initial emphasis on studies that are applicable across proposed facilities. The critical detector R&D areas have been identified as 4D tracking and vertexing, i.e. providing precision time and spatial measurements in a single detector unit, low-mass detectors, e.g. monolithic detectors that embed the electronics in the sensing elements, wireless data transmission technologies, implementation of advanced AI/ML algorithms in on-detector electronics, dual calorimetry among others, see Sec. 6.A.1.

The Energy Frontier also supports the possibility of a Higgs factory in the US. Given global uncertainties, consideration should also be given to the timely realization of a possible domestic Higgs factory, in case none of the currently proposed global options are realized.

6.6.3 The long-term-future Energy Frontier collider

In the long-term future we envision a collider that probes the multi-TeV energy scales, i.e. up to about hundred TeV center-of-mass energies. Its physics case rests on its ability to (1) produce the fundamental particles that generate the mechanism of electroweak symmetry breaking, (2) produce particles with flavor-dependent couplings to quarks and leptons, (3) search for thermal dark matter particles into the region of strong coupling in the dark sector, and (4) in general explore the unknown at the highest possible energy scale.

A 10-TeV scale Muon Collider with sufficient integrated luminosity provides an indirect energy reach similar or better to that of a 100 TeV proton-proton collider (e.g. FCC-hh, SppC), although its direct reach is limited to 10 TeV. The similarity between high energy lepton colliders (effectively $W - W$ colliders) and hadron circular colliders (effectively gluon-gluon colliders) is outstanding. Studies indicate that both the muon and hadron colliders have similar reach and can significantly constrain scenarios motivated by the naturalness principle. The 100 TeV hadron collider will have an advantage when it comes to searching for colored states, while the Muon Collider naturally has better access to EW states. Multi-TeV muon colliders will have the benefit of excellent signal to background ratios, taking advantage of the vector boson fusion production processes. As the multi-TeV colliders are planned for after the Higgs factory, they will benefit from the precision studies of the Higgs-boson properties in understanding the possible scale of new physics. One of the key measurements from the multi-TeV colliders is the one of the Higgs self-coupling to a precision of a few percent, and the scanning of the Higgs potential.

This program to enable new physics insight into higher scales is currently limited by technological readiness. In addition to the most prominent projects that have been proposed, i.e. hadron and Muon Colliders, other auxiliary proposals include high-energy e^+e^- colliders using plasma wakefield or structure advanced acceleration. All of these proposals require substantial accelerator R&D.

A vigorous R&D program into accelerator and detector technologies will be critical to position the US and international community at the forefront of this research on a long term. This R&D program must specifically enable instrumentation research that goes beyond current projects, so that the detector technology will be available to make use of these high-energy colliders once they can be built. The critical detector R&D areas have been identified as 4-dimensional tracking with precision timing detectors, small area silicon pixels in a high radiation environment. Besides that, particle flow calorimeters with hybrid segmented crystal, and fiber readout may offer a better alternative to silicon, see Sec. 6.A.1.

With the start of the Snowmass 2021 studies, there has been a surge in the interest of the US and the international community for the Muon Collider option because of advances in technology and analysis methodologies. There is synergy with the formation of the International Muon Collider Collaboration hosted at CERN. About a third of the contributed papers in the EF are on Muon Colliders. Since the last Snowmass study in 2013, there has been substantial progress in understanding the physics case, the detector requirements, as well as developing novel techniques to address the major beam induced backgrounds.

The investment in detector and collider R&D for hadron and muon facilities, and planning for discussion of siting options for Muon Colliders have to start now, and run in parallel with the HL-LHC and any e^+e^- precision electroweak program. Enabling this future, also requires strong input from every area of the theoretical community to understand the discovery potential of such colliders.

6.6.4 Opportunity for US as a site for a future Energy Frontier Collider

Our vision for the EF can only be realized as a worldwide program, and CERN as host of the LHC has been the focus of EF activities for the past couple of decades. In order for scientists from all over the world to buy into the program, the program has to consider siting future accelerators anywhere in the world. The US community has to continue to work with the international community on detector designs and develop extensive R&D programs, and the funding agencies (DOE and NSF) should vigorously fund such programs (as currently the US is severely lagging behind).

The US community has expressed a renewed ambition to bring back EF collider physics to the US soil, while maintaining its international collaborative partnerships and obligations, for example with CERN. The international community also realizes that a vibrant and concurrent program in the US in EF collider physics is beneficial for the whole field, as it was when Tevatron was operated simultaneously as LEP.

The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

Planning to proceed in multiple parallel prongs may allow us to better adapt to international contingencies and eventually build the next collider sooner. Such a strategy will also help develop a robust long term plan for the global HEP community. Therefore, there are requests to assess the cost of siting a linear e^+e^- Higgs factory collider option, and a multi-TeV Muon Collider in the US. In addition, to realize a successful US e^+e^- linear collider program, cost reduction options, and targeted accelerator R&D, e.g. for the Cool Copper Collider (CCC), is very important in the near term.

Some of the options listed above capitalize on the existing facilities, and on expertise in key areas of accelerator and detector R&D at Fermilab. Among other sites, Fermilab is proposed as an ideal one for a Muon Collider with a center-of-mass energy reach at the desirable 10-TeV scale. The synergy with the existing/planned accelerator complex and the neutrino physics program at Fermilab is an additional stimulus for such investment of effort. A roadmap of the accelerator R&D timeline, see Ref. [537] and Sec. 6.A.3, indicates that a 3 TeV Muon Collider is possible by 2045, though technically limited. A set of Muon Collider design options, with one of the siting options being at Fermilab, should be considered as an integral part of a global discussion for siting and selecting an international Muon Collider.

A goal should be to prepare a document summarizing design for the Fermilab-sited Muon Collider in time for the next Snowmass. Investment in this effort will reinvigorate the US high-energy collider community and enable much needed global progress towards possible discoveries at the next energy frontier.

The proposals and R&D efforts to address the innovative detector developments for Higgs factories are well underway globally and many challenges are resolved. Bold "new" projects such as a linear e^+e^- CCC, and a Muon Collider will offer the next generation some challenges to rise to. It will inspire more young people from the US to join HEP and in the long term help with strengthening the vibrancy of the field. Realizing our ultimate goal will require significant funding and government support. The community feels that there is potential to raise funds and obtain government buy-in for a future collider project located in the US. However, funding is not all that is needed. We also need a future program that continues to inspire the next generation of high energy physicists, and one that entices the next generation of graduate students to choose high energy physics as their field.

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6.A Appendices

This appendix presents the requirements, needs and challenges for the detector developments for future collider physics, including detection technologies, software and computing, event simulations and analysis techniques as well prospects for Monte Carlo event generators. In addition it discusses opportunities and challenges that the EF community will encounter in future EF projects, e.g. attraction and mentoring of young minds, diversity and inclusion, needed investments etc. The appendix ends presenting the timeline and expected costs of the major EF projects that were discussed in Snowmass 2021.

6.A.1 Detectors, reconstruction, simulation and data analysis

Enabling particle detection techniques, data computation and analysis methods, as well as precision calculations, event generators, detector and accelerator simulations are critical for any future project at the energy frontier.

Different collider projects have different requirements on detector layout and performance. For example, e^+e^- colliders require detectors with high granularity and low material budget, while hadron colliders have additional requirements on radiation tolerance for detectors to be placed close to the beam pipe. The detector design directly impacts the computational resources and affects the data analysis methodology. Needs for software and computing resources should be accounted for at the start of the detector design stage to inform an optimal design strategy and ensure the best possible physics performance of reconstruction algorithms. Requirements for computational resources are set by detector design parameters such as number of readout channels, luminosity, trigger system, data compression as well as the experimental computing model and the analysis methods. The sophistication of artificial intelligence and machine learning (AI/ML) techniques is growing ever more, and collider physics should continue to play a pioneering role in this expanding field of research by capturing and leading such developments. As we experienced at the LHC experiments, AI/ML techniques have become necessary tools to perform precision measurements and expand the reach of searches for new physics. We expect AI/ML techniques will play even greater roles at the HL-LHC and future colliders The direction of current research suggests that such techniques will be employed in future experiments not only in offline data analyses but also in online data selection and reconstruction, making their accuracy and reliability even more critical [7, 539].

Most measurements at high-energy colliders require the understanding of radiative corrections on observables. A close collaboration between theory and experiments is mandatory to design observables that have a reduced exposure to high-order effects and exploit detector capabilities as well as the latest developments in precision calculations and Monte Carlo simulations. A fundamental tool to design detectors, develop software and perform data analysis in all experiments is the Monte Carlo simulation of final state particles entering the detector. Essential software packages need to be supported to produce Monte Carlo samples, including

physics generators and the Geant4 detector simulation toolkit. The computational needs for such simulations strongly depend on the size of the MC samples, the complexity of the detectors, the precision and accuracy needed for the physics models embedded in these tools, as well as the data formats. For future collider feasibility and design studies, accelerator modeling is also of fundamental importance [7, 540].

Some of the most relevant aspects of needs for detector, method and tool development and research for the coming decade will be discussed in this subsection.

Detectors

Particle detectors are key to address science challenges and their development is based on our understanding of fundamental laws of physics. Therefore, there is a "virtuous cycle" between fundamental laws of nature and enabling detector concepts and techniques. Such virtuous cycle must remain strong and unbroken in order to lead to greater physics discoveries. In this context, detectors in high-energy physics face a huge variety of operating conditions and employ technologies that are often deeply intertwined with developments in industry. The environmental credentials of detectors are also increasingly in the spotlight.

At the EF, one can distinguish two major drivers for detector R&D: detector upgrades towards future hadron and Muon Colliders and development of advanced technologies for the future e^+e^- machines.

The detectors for the next e^+e^- Higgs factory must provide excellent precision and efficiency for all basic signatures, i.e. electrons, photons, muon and tau leptons, hadronic jets, and missing energy over an extensive range of momenta. The tracking resolutions should enable high-precision reconstruction of the recoil mass in the $e^+e^- \to Zh$ process for instance. These inherently very accurate physics requirements ask for integrated concepts with unprecedented precision, minimal power consumption and ultra-light structures. The demands for high resolution (granularity) and low material budget on one hand, and low power consumption on the other hand, exceed significantly what is the state-of-the-art today. Such leaps in performance can only be achieved by entering new technological territory in detector R&D. To quote just some examples, several new concepts for silicon sensor integration, such as monolithic devices, are being pursued for pixel vertex detectors, new micro-pattern gas amplification detectors (MPGD) are explored for tracking and muon systems, and the particle-flow approach to calorimetry promises to deliver unprecedented jet energy resolution [6].

The Basic Research Needs for High Energy Physics Detector Research & Development document (BRN in short) [541] compiles a list of requirements for transformative and innovative technologies at the next generation of energy frontier experiments focused on precision Higgs and SM physics, and searches for BSM phenomena, such as (1) low-mass, highly-granular tracking detectors and (2) highly-granular calorimeters, both with high-precision timing capabilities.

Emerging novel vertex and tracking detector technologies are the vital backbone for the success at a future electron-positron machines. These will operate in an environment with high (continuous or bunched) beam currents, a minimum distance from beam axis of about 20 mm, a requirement of $< 5\ \mu m$ single point resolution, high granularity ($< 30 \times 30\ \mu m^2$), power dissipation ($< 50\ mW/cm^2$), low mass (~ 0.1 % of X_0, or 100 μm Si-equivalent per layer). The clear challenge is unprecedented spatial resolution, to be achieved with ultra-small pixels, and thus extremely low material budget. Very thin detector assemblies are mandatory, while providing high stiffness and stability. The tracking resolutions should enable high-precision reconstruction of the recoil mass in the $e^+e^- \to Zh$ process, as shown in Table 6-14, and allow very efficient b and c tagging and tau-lepton identification through the reconstruction of secondary vertices. The detector solenoid magnetic field must be limited to 2 T for the Tera-Z operation at future circular electron-positron colliders, to avoid a blow up of the vertical beam emittance and a resulting loss of luminosity. The

2 T magnetic field limit is not a significant problem since the momentum scale of the produced partons is typically distributed around 50 GeV and does not exceed 182.5 GeV.

Table 6-14. *Physics goals and detector requirements [541, 542].*

Initial state	Physics goal	Detector	Requirement
e^+e^-	hZZ sub-%	Tracker	σ_{p_T}/p_T=0.2% for $p_T < 100$ GeV $\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}$/ GeV for $p_T > 100$ GeV
		Calorimeter	4% particle flow jet resolution EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2 EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ shower timing resolution 10 ps
	$hb\bar{b}/hc\bar{c}$	Tracker	$\sigma_{r\phi} = 5 \oplus 15(p \sin\theta^{\frac{3}{2}})^{-1} \mu$m 5$\mu$m single hit resolution
pp-100 TeV	Higgs	Tracker	σ_{p_T}/p_T=0.5% for $p_T < 100$ GeV $\sigma_{p_T}/p_T^2 = 2 \cdot 10^{-5}$/ GeV for $p_T > 100$ GeV 300 MGy and $\approx 10^18$ n$_{eq}$/cm^2
		Calorimeter	4% particle flow jet resolution EM cells 0.5×0.5 cm^2, HAD cells 1×1 cm^2 EM $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ shower timing resolution 5 ps 4 MGy / 5 GGy and $\approx 10^16/10^18$ n$_{eq}$/cm^2 central/forward
μ	Higgs & LLP	Tracker	30 ps timing resolution and 0.01 rad angular resolution 5μm single hit resolution

Gaseous and semiconductor detectors are the two main types of tracking detectors; other ones include fiber-based or transition radiation tracking devices. While gaseous detectors offer sizeable low-mass volumes and many measurements require an excellent pattern recognition and ultimate dE/dx measurement (e.g. cluster counting technique can be exploited instead of the charge-analog information), the silicon-based approach offers the most accurate single point resolution. The breakthrough technology is expected to come from monolithic devices incorporating complex readout architectures in CMOS foundries. To minimize material budget, new technologies, like stitching, will allow developing a new generation of large-size CMOS MAPS with an area up to the full wafer size [543, 544]. In addition to large-size sensors, it may also be useful to bend thin (50 μm) sensors to make cylindrical assemblies. Fast picosecond-time sensors based on Low-Gain Avalanche Detectors (LGAD) [545] and 3D-devices can be also exploited. Aiming for an excellent position and timing resolution ($\sim$ 10 ps and $\sim$ 10 μm) with GHz counting capabilities to perform 4D tracking, LGAD-based technologies represent a very attractive option for PID and TOF applications. For future applications at the EF, alternative technologies include beyond state-of-the-art interconnection technologies, such as 3D vertical integration, through-silicon-vias (TSV), or micro bump-bonding, which, while retaining the advantages of separate and optimized fabrication processes for sensor and electronics would allow fine pitch interconnects of multiple chips.

The "particle flow" (PFlow) concept, originally developed for the electron-positron Linear Collider (LC), aims at measuring the energy of all the particles in a jet, exploiting track information for the charged particles, ECAL for prompt photons, and HCAL to capture the neutral hadrons. Due to this, PFlow has led to calorimeter designs, as part of a complex system of inter-connected detectors rather than as a stand-alone device. Present and future challenges in calorimeters are closely linked to all aspects of ultimate exploitation of the PFlow technique and the dual-readout calorimetry [546] approach, developed by the RD52, DREAM, IDEA and CalVision collaborations. Silicon photomultipliers have seen a rapid progress in the last decade,

becoming the standard solution for scintillator-based devices, but also enabling substantial improvement in dual-readout calorimetry, based on scintillating and clear plastic fibers embedded in absorber structures. Ultra-fast timing in calorimetry can be also used to resolve the development of hadron showers, by separating their electromagnetic and hadronic components, and therefore simplifying the implementation of the particle flow algorithm. In general, space–time tracking could be used in many physics analysis at LHC – Higgs, BSM searches for long-lived particles, by measuring precisely the time-of-flight between their production and decay, and/or in assigning beauty and charm hadrons to their correct primary vertex. An ultimate concept is to develop 4D real-time tracking system for a fast trigger decision and to exploit 5D imaging reconstruction approach, if space-point, picosecond-time and energy information are available at each point along the track.

An emerging effort during Snowmass has focused on strange-quark tagging [53]. Particle identification at high momenta could further boost strange tagging capabilities at future e^+e^- machines as well as the analysis sensitivity in constraining the available phase space for new physics. Gaseous Ring Imaging Cerenkov system (RICH) detector can be capable of π/K separation up to 25 GeV. A preliminary study based on ILD geometry at ILC, shows that in a compact RICH with a radial extension of 25 cm, the Cherenkov angle resolution can be maintained at the level of $\sim$5 mrad in magnetic fields up to 5 T. This leads to a discrimination power of 3σ between kaons and pions up to momenta of approximately 25 GeV. Further simulation studies and system optimization are needed to evaluate globally the impact of a RICH system on object reconstruction, such as PFlow jets, and on other physics benchmarks, when used in conjunction with silicon tracking detectors.

Future hadron collider experiments have an additional requirement of radiation hardness. The radiation levels close to the beam pipe will require technologies that can withstand radiation levels that are an order of magnitude higher than those expected at the HL-LHC. Such demanding requirements urge a long term R&D on radiation-tolerant technologies, especially for tracking systems. In addition, both hadron and Muon Collider experiments need to use fast-timing detectors to suppress backgrounds. More specifically, a factor-of-five larger pileup at a 100 TeV hadron collider than at the HL-LHC is expected to pose stringent requirements on the detector design [547]: future hadron colliders need timing of the order of 5-10 ps per track to suppress pileup and correctly assign tracks to vertices. At a multi-TeV Muon Collider to reject a good fraction of beam induced background, accurate timing information with a resolution of 30 ps is assumed to be available in the vertex detectors [542].

At future hadron colliders, detector capabilities to reconstruct highly boosted objects are fairly challenging (for instance, the average Z boson from ZZ production would shower mostly within a single LHC calorimeter cell). This challenge is accentuated by so-called "hyper-boosted" jets, whose decay products are collimated into areas the size of single calorimeter cells. Holistic detector designs that integrate tracking, timing, and energy measurements are needed to mitigate for these conditions [214,548–552]. Hadronic and electromagnetic shower components up to several TeV need to be simulated, where extrapolations to these high energies come with large uncertainties. Differences in the hadronic shower simulation models in Geant4 [553] have been reported for pions in the energy range 2–10 GeV [554]. Detailed studies of hadronic showers will be needed in the next few decades to achieve the best possible precision in QCD measurements at future colliders.

While research has always required state-of-the-art instrumentation in trigger and data acquisition systems, the demands for the next generation of hadron colliders are the increasingly large local intelligence, integration of advanced electronics and data transmission functionalities (e.g. using FPGA). Another important trend is the progressive replacement of the complex multi-stage trigger systems by a new architecture with a single-level hardware trigger and a large farm of computers to make the final online selection and to reduce Level-1 trigger rate to O(kHz) for permanent storage. A technical challenge is also associated to run both online trigger algorithms and offline reconstruction on heterogeneous computing platforms, including GPUs and FPGAs, for which code portability to multiple computing platforms is a challenge to be resolved. This illustrates the need to bridge the gap between computing needs and available resources, at least in an immediate future, as well as the trend towards moving more complex algorithmic processing into the

online systems. Modern technologies allow the integration of significant intelligence at the sensor level and many different R&D lines are being explored, like local hit clustering for strip and pixel detectors, local energy summing for calorimeters, local track-segment finders. The use of advanced ML algorithms, such as neural networks (NN), boosted decision trees (BDT) and many others, is a long-standing tradition in particle physics since 1990's and has been already key enabler for discoveries (e.g. single-top production at Tevatron). Bringing the modern algorithmic advances from the field of ML from offline applications to online operations and trigger systems is another major challenge.

As the high-energy particle physics community and particularly the Snowmass community begins to design future detectors, it is important to keep the many, varied LLP signatures in mind, lest we design new detectors that are biased against them. For example, overly-aggressive filtering can introduce biases that limit the acceptance for displaced tracks [555]. At the same time, we can develop technologies, such as dedicated trigger algorithms [556], displaced tracking algorithms [557], and timing detectors [320, 558], to explicitly reconstruct and identify LLPs. Careful studies of beam-induced backgrounds will be necessary to reduce and/or quantify these background contributions without removing possible LLP signals. Other important factors to consider for LLPs include the time between collisions and how that interplays with the detector readout, as well as the size of the beamspot, the amount of pileup and the material budget of the detector areas closest to the interaction point.
Different geometry choices that provide similar hermeticity for prompt particles can differ drastically in their ability to reconstruct particles that do not originate from the interaction point. In particular, high granularity at large radii enables better reconstruction efficiency of displaced tracks and vertices, and helps to distinguish them from beam-induced and non-collision backgrounds.
A high volume, (partially) shielded subdetector system like the current muon systems at LHC experiments would therefore play an important role in searches for LLPs at future hadron colliders. For a future e^+e^- collider, on the other hand, the background yields are expected to be much lower and it could be beneficial to invest the equivalent amount of space into a larger inner detector, and restrict the muon system to the minimum required for muon identification. Finally, Muon Colliders [39] come with a new set of challenges for LLP searches, as their detectors are bombarded from both sides with ultrahigh energy electrons/positrons from the in-flight decay of the muon beam [555, 559]. It is difficult to shield the detectors from this qualitatively new beam background, but over 99% background rejection can be achieved by making use of timing and angular measurements from paired layers [559]. Whether simultaneously a good signal efficiency for LLPs can be maintained needs to be studied further.

Future collider detectors will also face a large number of diverse engineering challenges, in the areas of system integration, power distribution, cooling, mechanical support structures, and production techniques. Within the field of particle physics, technologies developed under generic R&D studies or with the aim to address experiment-oriented challenges at future colliders provide a boost in innovation and novel designs that often suit the needs of the Intensity or Cosmic Frontiers, i.e. neutrino or astroparticle physics.

Monte Carlo Event Generators

Nearly all high-energy experiments rely on the detailed modeling of multi-particle final states through Monte Carlo simulations [560]. A particular strength of general-purpose simulation tools derives from the factorization of physics effects at different energy scales, making their underlying physics models universal. Uncertainties on experimental measurements are often dominated by effects associated with event modeling. These uncertainties arise from the underlying physics models and theory, the truncation of perturbative expansions, the parametrization or modeling of non-perturbative QCD effects, the tuning of model parameters, and the fundamental parameters of the theory. Addressing and reducing the uncertainties is crucial to meet the precision targets in current and future measurements.

The experimental facilities discussed in this report span a wide range of energies, beam particles, targets (collider vs. fixed target), and detected final states. Each experiment may require some dedicated theory input to the simulation, such as high-precision QED calculations for Tera-Z or an electroweak parton shower for a Muon Collider. Other aspects, such as parton-to-hadron fragmentation or hadronic transport models can be similar for many facilities, enabling the modular assembly of (parts of) a generator from existing codes when targeting a new facility. In this manner, previously gained knowledge and experience can be transferred, and a more comprehensive understanding of the physics models is made possible by allowing them to be tested against a wealth of data. These cross-cutting topics in event generation have been identified as a particular opportunity for theoretical developments in a broad HEP program [560].

The extraction of SM parameters at the HL-LHC will depend on the precision of perturbative QCD and EW calculations, both fixed order and resummed, and on their faithful implementation in particle-level MC simulations. The results of some analyses will however also be limited by the number of Monte Carlo events that can be generated, and computing efficiency will play a crucial role. Future highest-energy colliders, including a potential Muon Collider, will likely require electroweak effects to be treated on the same footing as QCD and QED effects.

The Forward Physics Facility at the LHC will leverage the intense beam of neutrinos, and possibly undiscovered particles, in the far-forward direction. These measurements will require an improved description of forward heavy flavor – particularly charm – production, neutrino scattering in the TeV range, and hadronization inside nuclear matter, including uncertainty quantification [158].

Future lepton colliders would provide permille level measurements of Higgs-boson couplings, and will reach even higher precision in the measurement of the W-boson mass (one part in 10^{-6}) and the top-quark mass (one part in 10^{-4}). The unprecedented experimental precision will require event generators to cover a much wider range of processes than at previous facilities, both in the Standard Model and beyond. In addition, predictions for the signal processes must be made with extreme precision, involving QED up to fourth and EW corrections up to second order. Some of the related methodology is available from the LEP era, while other components will need to be developed from scratch.

With the next generation neutrino experiments not being limited by statistical uncertainties, and all running and planned experiments using nuclear targets, one of the leading systematic uncertainties to their measurements arises from the modeling of neutrino-nucleus interactions. This requires the use of state-of-the-art nuclear-structure and -reaction theory calculations. While not a traditional topic for general-purpose high-energy event generators, there is strong overlap with topics relevant to simulating high-energy neutrino DIS in the FPF detectors and at IceCube. This is expected to become an area of active development and cross-collaboration between frontiers.

The EIC will use highly polarized beams and high luminosity to probe the spatial and spin structure of nucleons and nuclei. Simulating spin-dependent interactions of this type at high precision is currently not possible with standard event generators and requires the development of new tools at the interface between particle and nuclear physics. It is expected that measurements at the LHC can greatly benefit from these developments [259, 561]. Various experiments also require the understanding of heavy-ion collisions and nuclear dynamics at high energies as well as intricate heavy-flavor effects.

In addition to the physics aspects, there are similar computational aspects, such as interfaces to external tools, handling of tuning and systematics, data preservation, the need for improved computing efficiency, and connections to artificial intelligence and machine learning [562]. The following sub-section will present the computational requirements at future experiments. In the context of preparing to fulfill the needs for MC samples in near-future and far-future EF programs, it should be highlighted that the MC event generation processes, especially at hadron colliders when high-order QCD corrections are included, are very

CPU-intensive, and the Geant4-based detector simulation applications are among the largest consumers of computing resources at the HL-LHC. Therefore, it is important to develop new and faster computational techniques for MC event generation and support detector simulation applications to maintain and improve the accuracy of physics modeling at future collider experiments [540].

Computational requirements

Experiments require computational resources during their design, operation, and data analysis phases. Experiments must generate and simulate collision events and other backgrounds, reconstruct events, optimize their design, trigger on collisions, reconstruct events, calibrate the experiment, and analyze the reconstructed data to extract physics.

Software trigger systems are ubiquitous for hadron collider detectors, which face significant data reduction challenges even before recording events to long-term storage. Such triggers are large computing farms that must execute a pared-down reconstruction of high multiples of the eventual recorded event rate in real time, and hence typically constitute very powerful computing sites on their own which can be repurposed when collisions are not being recorded. The challenges of offline reconstruction and software triggering go hand-in-hand.

There are many physical resources that are needed — long-term storage, both "hot" and "cold" (today represented by disk and tape); computers, both traditional CPU and accelerators like GPUs; and network bandwidth. Given the speedy evolution of computing, it is hard to predict what mixtures of available technologies will be optimal on the timescale of new energy frontier experiments. Nevertheless the scale of the computing problems posed by proposed facilities is roughly indicated by the data volume of the experiments. Estimates are summarized in Table 6-15. FCC-hh is the only facility with offline data sizes exceeding those of HL-LHC by more than an order of magnitude.

Table 6-15. *Computational resources expected at future Energy Frontier colliders.*

Collider Scenario	Event size	Event rate	Data/year
HL-LHC general purpose expt	4.4 MB	10 kHz	0.6 EB
FCC-ee Z-pole, one expt	1 MB	100 kHz	2 EB
CEPC 240 GeV, one expt	20 MB	2 Hz	260 PB
ILD 500 GeV	178 MB	5 Hz	14 PB
CLIC 3 TeV, 1 expt	88 MB	50 Hz	110 PB
Muon Collider, 1 expt	50 MB	2 kHz	2 EB
FCC-hh, 1 expt	50 MB	10 kHz	10 EB

MC simulations, including event generation, detector simulation and event reconstruction, generally constitute the majority of offline computing and hot storage use by experiments. For example, ATLAS projections for HL-LHC anticipate $\approx 70\%$ of CPU and $\approx 60\%$ of disk use to arise from MC simulation [563, 564]. More specifically, the CPU consumption in ATLAS is dominated by the detector simulation that is driven by the complex geometry of the calorimeter and the event generation is the second-leading contribution, whereas in CMS the event reconstruction is the dominant contribution while the detector simulation and event generation constitute the second and third contributions respectively. In general the proportion of resources for MC simulations is expected to be even higher for lepton colliders, due to the more democratic cross sections of relevant processes. Therefore efforts to maintain or increase the physics precision and accuracy of MC event generators and Geant4 physics models while speeding up the code utilizing computing hardware

accelerator and machine learning techniques and specialized hardware should be aggressively pursued, given their major impact in our ability to extract physics from near-future EF programs and future facilities.

The optimal way to provision the required resources will likely evolve over time. Trigger farms will still need to be located in physical proximity to experiments due to latency requirements, but offline processing may take additional advantage of resources that are shared with other sciences (such as supercomputing centers) or which are provided by industry (cloud resources). The design of experiment computing architectures will be influenced by the cost structure and technology availability imposed by such use.

The high energy physics community is already active in cross-collaboration forums such as the HEP Software Foundation [7, 565, 566] to find solutions that can meet the challenges brought forward by the amount of data delivered by HL-LHC and future colliders.

LHC experiments are also putting in place non-traditional analysis workflows and computing architectures [567] in order to exploit the physics potential of the data discarded by their triggers. For example, real-time analysis (Data Scouting in CMS, Turbo Stream in LHCb, and Trigger-level analysis in ATLAS) move part of the data reduction (reconstruction and calibration) into the trigger system, allowing data to be recorded with significantly lower trigger thresholds with negligible increase in bandwidth. These workflows can also exploit upgrades to the processing capabilities of trigger systems designed to tackle more challenging data taking conditions; for example, LHCb and CMS have begun to employ GPUs in their software trigger in Run-2 to parallelize problems such as particle tracking.

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and ML have come to pervade particle physics. Particle identification and event classification in data analysis and software triggering routinely use ML models. There are many proposals to extend the use of AI/ML in other realms which are just beginning to be explored, and we mention a few examples below, and for a comprehensive review we refer to the Snowmass 2021 Computational Frontier report [7].

The ability to find unexpected deviations from the Standard Model — and not just classify signals from specifically-targeted processes — has been a goal in the field for a long time and is important for fully exploiting the datasets collected by new facilities. Efforts are underway using a number of techniques to try to find such events, using semi-supervised and unsupervised learning methods. Such methods could be implemented at the data analysis level or even earlier in the trigger system. Similar anomaly detection techniques can also improve effective operation of experiments by rapidly identifying periods of bad data. Algorithms that can be used for identifying outliers can also learn the optimal way to compress data with tolerable losses in fidelity, and studies are in progress to assess how these can be employed for HL-LHC and future colliders.

Work is in progress in the US and internationally to provide tools to transform ML models into FPGA code. This opens the door to deploying ML in hardware triggers, improving signal discrimination for experiments (especially at hadron colliders) with strong bottlenecks at this level. Closely related to this area of research is the development and testing of a computing model for optimal utilization of modern computing hardware platforms. More specifically, the development of portable code that runs on multiple computing hardware platforms, both locally and remotely, is a necessary step towards utilizing the available computing resources when running ML algorithms [539].

Generative ML techniques hold the potential to accelerate event generation and simulation. By learning accurate approximations to a full physics model that can be executed much faster, generative ML can

increase the amount of Monte Carlo that can be produced with limited computing resources, improving the optimization of analyses and final statistical uncertainties [562].

The core technology of model training (optimizing a function of many parameters relative to some objective) motivates the idea of "differentiable programming," in which more generic user code, written in an appropriate framework, can be rapidly optimized in a similar fashion if analytic derivatives are available. If deployed at scale, this opens the possibility of end-to-end optimization of data analysis and other computations, as well as more sophisticated methods of handling systematic errors.

Detector design is also an optimization problem. By linking together appropriate methods, it may be possible to do a practical end-to-end optimization of a detector from scratch using target physics measurements as the benchmark, rather than intermediate figures of merit for each subdetector (such as momentum or energy resolution). The simultaneous global optimization of detector designs could allow improved physics performance for reduced cost.

From a theoretical perspective, there are cases where it is possible to implement machine learning models that respect important symmetries by construction and are potentially capable of being mapped onto first-principles theory; such approaches may provide acceleration for otherwise computationally-difficult problems, or rigorous interpretability. The use of neural networks for tackling inverse problems (determining regions of theory space that are compatible with observation) is another promising direction at this interface [562].

As it is the case with other data selection and data processing tools used in high energy physics, cross-collaboration and cross-field activities should be encouraged. Challenges such as having the shortest possible time-to-insight on large amounts of data, and extracting small signals from large backgrounds, are not unique to high energy physics. Developing and discussing solutions for similar problems in different fields can be mutually beneficial. Computer science and industry are routinely developing ML algorithms, tools and hardware beyond the state-of-the-art, and their involvement in high energy physics projects can accelerate the field's development.

Analysis reinterpretation, preservation and open data

Preservation of experimental data, simulation, software and analysis products is necessary to ensure a long-term return on investment in the EF (and in general in other Frontiers). FAIR principles (Findability, Accessibility, Interoperability, and Reuse of digital assets) [568] should be used as guidance not only for data but also for research software. This approach allows for reproducible scientific results, that in turn can facilitate and enable new analyses and can be easily reinterpreted under different theoretical hypotheses.

In order to make this possible, the Computational Frontier recommends that:

- current and future experiments have a strategy and sufficient resources to preserve data and analysis capabilities, including beyond their lifetimes;
- substantial investments are made to support efforts on FAIR data and analysis preservation. This also includes theoretical inputs, statistical analysis, AI models, metadata, archives etc. The careers of those working on these topics should be equally supported.

International coordination with current and future particle and astroparticle physics consortia such as the European Science Cluster of Astronomy and Particle Physics ESFRI research infrastructures [569] (including the HL-LHC) can help adopting these recommendations, given that multiple funding agencies worldwide require data and analysis preservation, as well as open data and research products.

In terms of making experimental data publicly accessible (Open Data), future experiments at the EF can discuss future policies together with other communities (e.g. Cosmic Frontier) where opening the data is common practice, in order to understand how to balance the needs for recognition of the scientists producing the data with the growing requirements to make the data available, as well as the challenges that opening data entails in terms of physics analyses that are not done under the careful scrutiny of the collaborations. It would be desirable for future EF experiments to design Open Data policies starting from the beginning of their life cycle, also taking inspiration from the experience and examples within the CERN experiments [570].

6.A.2 Enabling the Energy Frontier research

This section attempts to address from the point of view of the EF community several broad questions that pertain the whole HEP community, such as opportunities and challenges in future collaborations, how to build a cohesive and diverse community, and expected needed investments to prepare for major future experiments.

Collaborations

What opportunities exist for cross-frontier, cross-disciplinary, or international collaboration and cooperation in the coming decade to enhance our ability to address the issues identified (including training or mentorship) ? How do these collaborations affect the timescales or resources needed for these activities ?

The EF community in the US is fully integrated in and interdependent with the broad international community of particle physicists, which includes experimentalists, theorists, accelerator and detector physicists in the various domains that pertain to HEP as well as nuclear physics. The cross-fertilisation between different domains of particle physics is a strength of the EF and will continue to offer opportunities in the future, thus has to be nurtured and supported.

Interdependence between Frontiers. Given the strong dependence of the EF on collider technology, there is a unique opportunity for collaborations with the Accelerator Frontier. We have seen growing interest in the EF community for the development of collider technologies that enable the targeted physics research.

There is a clear interdependence between the communities of experimentalists and theorists. Such interdependence offers an opportunity for the EF and Theory Frontier to work hand-in-hand on physics studies for the next generation of collider physics experiments.

At the LHC we already experience a strong cross-fertilization between the EF and the Rare Processes and Precision Measurements Frontier. Such cooperation will be even more useful and necessary in the HL-LHC and at future colliders to tackle experimental and theoretical challenges, for example on detector solutions as well as analysis and computational methods and techniques. On the latter, the cooperation with the Instrumentation and the Computational Frontiers is instrumental for the development and eventual use of transformative technologies that will enable the realization of novel detectors we well as readout, reconstruction and simulation techniques for future collider experiments.

The EF must keep working in concert with the Theory, Rare Processes and Precision Measurements, Cosmic, and Neutrino Frontiers to discover particle dark matter and probe its interactions with the SM at future

collider experiments. Sections 6.3.1.2 and 6.5.5 provide examples of how searches for invisible particles with future experiments at the energy frontier are a vital complement to the efforts in the other frontiers. Collider experiments offer unique possibilities for new physics discoveries as well as the ability to connect signals of astrophysical DM observed at the other frontiers with measurements of the fundamental interaction(s) that are responsible for such signals. To highlight this complementarity that is central to understanding the nature of DM, representatives from the different frontiers developed the Snowmass 2021 Dark Matter Complementarity report [478].

Interdependence between US and international communities. The US community in the EF is fully embedded in the international community. Mutual support and exchanges of ideas, expertise and future plans is advisable and inevitable. The growth of one member of the community is the growth of the whole community. Constructive and multi-directional communication within the broad international community is vital to keep the field vibrant and make concrete scientific progress.

Cross-fertilization between Energy Frontier and other domains of physics. The planned construction of EIC in the USA within the next decade offers a unique opportunity for strengthening the central role of the US scientific community in the field of particle physics, seen as a whole. The consideration of EIC, within the EF Topical Groups for this Snowmass study, has been instrumental in fostering opportunities for cross-fertilization between the two fields of HEP and Nuclear Physics in terms of physics, experimental technologies, data analysis techniques and methods, as well as theoretical and phenomenological tools. The two (international) communities are well integrated, beyond the artificial and too-often restricting boundaries set by funding agencies.

Emerging technologies and detection techniques in other realms of physics, e.g. quantum computing and detectors, novel materials, new detection techniques and methods, including AI/ML etc. will offer new opportunities for enhancing our experimental capabilities in ways that can be difficult to predict with our current knowledge.

Building a diverse Energy Frontier community

How can we ensure that the US particle physics community is vibrant, inclusive, diverse, and capable of addressing the scientific questions identified, and of fulfilling our obligations to society during this period ?

A vibrant, inclusive, diverse and capable scientific community are necessary for any success of the US scientific community in the EF. These can be achieved by innovation as well as empowerment and training of the next generation of leaders in the EF.

Continue to innovate and empower. A vibrant EF community requires a large base of well motivated early career scientists with a vision for the future of the field. Such motivations and vision are acquired by training, mentorship, and empowerment. The complexity of modern experiments and the dispersion of large collaborations too often prevent young scientists from developing a vision and solid foundation in different sectors, as they are often confined in specific niches of their research. It is important for young scientists to participate in different and diverse collaborations, similar to the variety of scientific methods and techniques they engage in.

In large collaborations such as those at the LHC, the contribution to specific research is often hidden by large author lists in papers or conference presentations given by people who did not directly participate to

the presented studies. In addition, too often students do not have an opportunity to present their analyses at a conference during the course of their studies due to the complex decision making process of the speaker committees. The main vehicle for an early career physicist to get visibility inside and outside the collaboration is by appointments in managerial roles such as subgroup or group convenorship, which has become a coveted (instead of longed-for) role by young physicists and used as a trampoline for a permanent job. Such strict hierarchy and opaqueness of large collaboration often causes lack of ownership of projects and physics studies by early career physicists. A more transparent and merit-based empowerment of early career scientists will help the community grow in the long term.

Inclusiveness and diversity are at the core of the scientific endeavor, which is motivated solely by the goal of advancing fundamental scientific knowledge with a potential societal impact.

By pursuing our goals of fundamental knowledge at the energy frontier we will inevitably continue to push the boundaries of innovation in several areas of research and we will fulfill our obligations towards society, not only with augmented knowledge but also with concrete technological advances.

Training the next generation of scientists. The EF experiments are the largest scientific experiments in the world and offer young researchers unique exposure to open research within diverse international collaborations. Junior scientists engaged in particle physics research receive hands-on training in quantitative, computational, engineering domains as a part of their work on big collider data. The EF community has been pioneering new technologies and methods (both theoretical and experimental) that have found applications in a variety of scientific fields that greatly benefited society as a whole. The Energy Frontier has a long-standing record of training young scientists. Keeping this tradition is of paramount importance as it is necessary to keep the field thriving. There is a unique opportunity to engage early career scientists with challenging new problems on physics prospects for future colliders, detector design, software development, analysis and computational techniques. The vast range of challenges that we face at future colliders are the perfect training ground for future scientists.

Investments essential to the progress of the Energy Frontier

What investments need to be made during 2025-2035 for the continuing scientific, technical, or community progress identified by your frontier in the decades beyond, on what timescales can these be implemented, and what resources would be required ?

The realization of the EF scientific program depends on transformative advances in several critical areas of research, such as innovation in collider and detector technologies, use and development of cutting-edge computational and data acquisition techniques as well as novel theoretical ideas and accurate calculations. These areas of research need significant and immediate support and investment in order to accomplish the energy frontier programmatic goals and have a competitive scientific community in the next decade. The resources to be allocated will have to be commensurate to the vast range and amount of scientific output that is expected by those experiments. Such a scientific output is not only measured in terms of scientific articles and size of the community, but also in terms of the societal impact that can be considered as a return of investment, such as training of young professionals, dissemination of scientific knowledge, development of new technologies and methods, etc. History has demonstrated that the activities of the Energy Frontier community have always had large societal return of investment, therefore the resources allocated to such enterprises should be commensurate to their expected return.

- **Collider R&D:** progress in the energy frontier is dependent on progress in collider technologies. It is vital for future energy frontier experiments to secure support for collider R&D that enables

transformative changes in accelerator and magnet technologies in the next decade, for electron, hadron, and Muon Colliders.

- **Detector Technology R&D:** as the 2020 BRN [541] report identified, there is an opportunity to capture advances in detector technologies, e.g. for low-mass and high granularity detectors, to use at future electron colliders. In parallel there is the need at future hadron and Muon Colliders for innovative technologies that can withstand an unprecedented level of harsh environmental conditions.

- **Computing Resources:** computing is a fast-evolving field, mostly driven by industry. However, HEP has historically pioneered techniques, e.g. ML, and has developed its specific solutions to its specific computational and data acquisition requirements. While it is difficult to predict advances in such a dynamic field in the next decade, we surely know that we have an opportunity to capture and lead the progress in computing for the next generation of accelerator-based experiments. For example, while lepton colliders do not provide the same computing challenges as hadron colliders, the sheer amount of channels and information to be analyzed requires the use of cutting-edge computational resources for all proposed collider experiments. Not to be forgotten is the ever growing computational need in theoretical calculations and simulations.

- **Theoretical Physics:** Advances in theoretical calculation and modeling for new physics are expected to maintain an important role in the unveiling of new opportunities for experimental measurements and searches for new physics beyond the Standard Model. As the experimental measurements become more precise, theoretical calculations need to become more accurate. In the past decade we have seen transformative advances, often called 'revolutions', in theoretical calculations and Monte Carlo simulations that allowed to achieve unprecedented levels of precision in measurements that are dominated by theoretical or modeling uncertainties, and extended the reach of searches at the HL-LHC. Similarly, we have a unique opportunity to capitalize on the expected progress in the next decade. For example, at e^+e^- colliders, where extremely high precision is expected to be reached in a broad range of experimental measurements, high-order calculations as well as fast and accurate Monte Carlo simulations are needed to match that precision. In another direction, as shown in a number of examples in this report as well as in the report of the Theory Frontier [5], theorists have discovered new ideas in QFT and model building which have led to new observables and clarified the meaning of others in the quest for new physics. For example in Higgs-boson physics, contributions from theory have been crucial to build a precision physics program and have led to qualitative changes in studying the possibility of an electroweak phase transition, new ideas for investigating the relation between the Higgs boson and the flavor dynamics of fermions, and EFT techniques that have all broadened the experimental program. Therefore, continued investment in theory is crucial to the success of the EF.

6.A.3 Timelines and Costs of Proposed Future Colliders

The projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options, such as ILC sited in Japan, CepC in China, LHC, HL-LHC, CLIC and the integrated FCC option considered during Snowmass 2021, are shown in Fig. 6-40. The yellow bar shows the time needed for preparation and R&D, prior to construction or transformation that are represented by the red bar. The green and blue boxes represent electron and proton colliders respectively, together with the operating center of mass energy and the integrated luminosity.

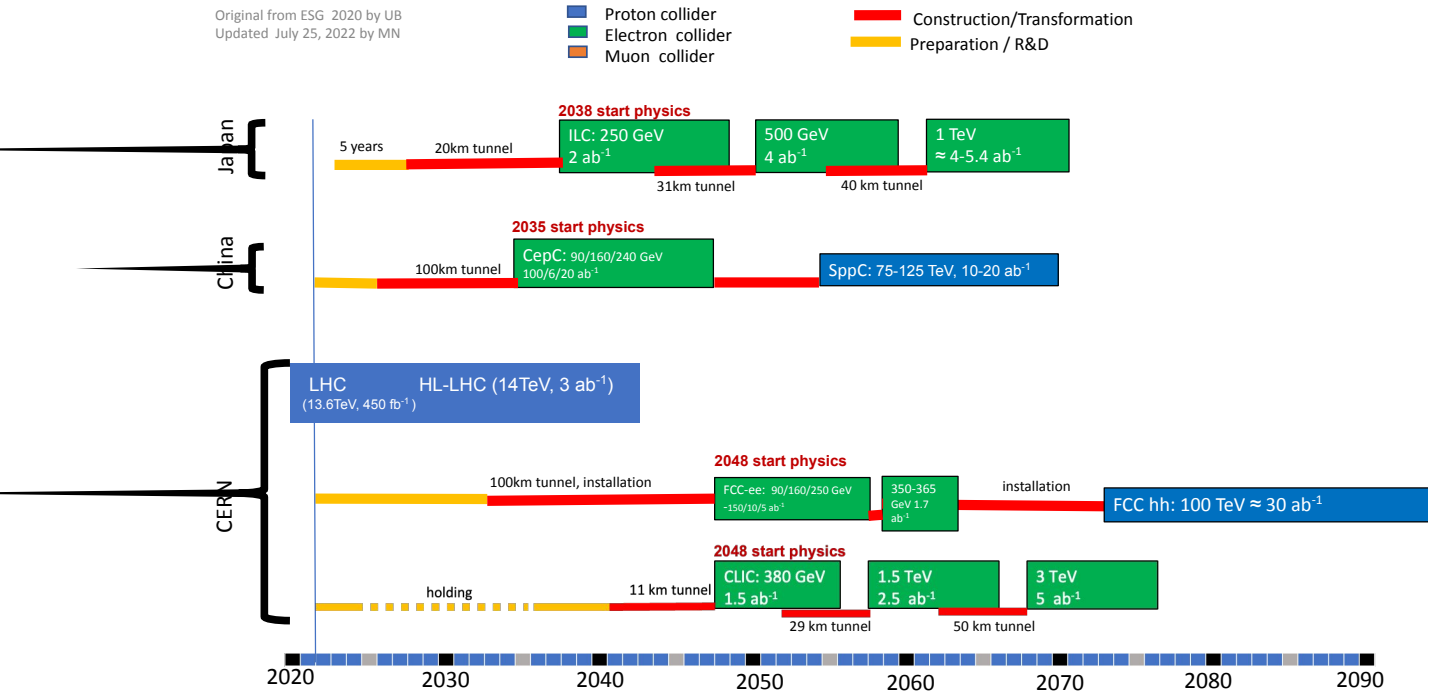

Figure 6-40. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*

Timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option are shown in Fig. 6-41. It is important to note that the timelines shown are technologically limited, and some challenges need to be sorted out, for example, successful R&D and feasibility demonstrations for CCC and Muon Collider are essential at a short timescale. Additionally, evaluation progress in the international context and discussion on international cost sharing is a top priority.

Cost estimates, construction start and end dates for the large future collider projects are summarized in Table 6-16. Costs are taken from the collider Implementation Task Force (ITF) report [1] by the Accelerator Frontier. Please refer to the ITF document for explanations on how they were estimated and associated caveats.

The R&D cost estimates for medium-scale projects and near-term suggested contributions to be considered by U.S. EF community (and proponents of the options) are listed in Table 6-17. In the spirit of Snowmass, such numbers are to be taken as an approximate scale of investments.

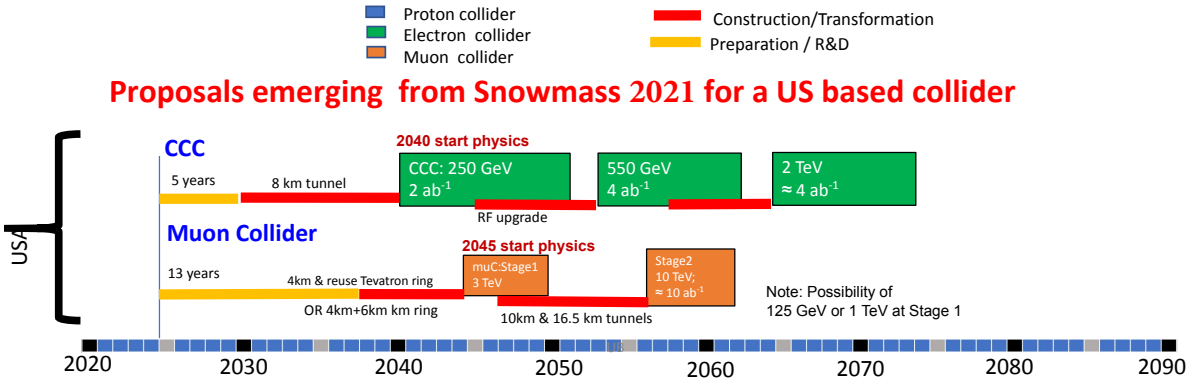

Figure 6-41. *Approximate timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option.*

Table 6-16. *Cost estimates, construction start and end dates for the large future collider projects.*

Project	Construction		
	Start date (yr)	End date (yr)	Cost B$
Higgs Factories			
CepC	2026	2035	12-18
CCC (higgs Fac)	2030	2040	7-12
ILC (higgs Fac)	2028	2038	7-12
CLIC	2041	2048	7-12
FCC-ee	2033	2048	12-18
Multi-TeV Colliders			
Muon Collider (3 TeV)	2038	2045	7-12
Muon Collider (10 TeV)	2042	2052	12-18
SppC	2043	2055	30-80
HE CCC	2055	2065	12-18
HE CLIC (3 TeV)	2062	2068	18-30
FCC-hh	2063	2074	30-50

Table 6-17. *Suggested R&D investment to be considered by the U.S. EF community with approximate start and end dates.*

Project	R&D		
	Start date (yr)	End date (yr)	Cost M$
Higgs Factory detector R&D	now	2035	100-150
CCC higgs factory	2024	2028	100
CCC High Energy	2045	2050	200
Muon Collider (1-3 TeV)	now	2040	300
Muon Collider (10 TeV)	2040	2047	200

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7

Instrumentation Frontier

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Executive Summary

While the fundamental science questions addressed by HEP have never been more compelling, there is acute awareness of the challenging technical constraints when scaling current technologies. Furthermore, many technologies are reaching their sensitivity limit and new approaches need to be developed to overcome the currently irreducible technological challenges and to cope with ever increasing extreme data volumes. For the field of HEP to continue to have a bright future, priority within the field must be given to investments in both evolutionary and transformational detector development that is coordinated across the National Labs and with the university community, international partners, other disciplines and industry. This situation is unfolding against a backdrop of declining funding for instrumentation, both at the National Labs and in particular at the universities. This trend has to be reversed for the country to continue to play a leadership role in particle physics. In this challenging environment it is essential that the community invest anew in instrumentation and optimize the use of the available resources to develop new innovative, cost-effective instrumentation. We need to invest in modernized facilities with enhanced capabilities, address intermediate planned project needs, and carry out blue-sky R&D that enable new physics opportunities to successfully accomplish the mission of HEP. Many of the findings of this Snowmass report are still well aligned with the 2019 Report of the Office of Science Workshop on Basic Research Needs for HEP Detector Research and Development (BRN report) [1], but some additions and updates have been identified.

Much of the HEP portfolio is dominated by mid-sized to large scale experiments, which take decades to design, build and operate, and often span the entire lifetime of individuals' careers. In this environment it is becoming increasingly difficult for students and young researchers to have the opportunity to learn hands-on about detector instrumentation. For example on the collider physics side, where in addition to shortages in coverage of detector operations expertise, there will be potentially a large gap in time between the current High Luminosity Large Hadron Collider (HL-LHC) upgrades finishing and concrete designs and construction for the next generation collider experiments starting. The key challenge here will be to maintain the technical skills and experience within the community, and to train a new generation of instrumentation experts. This gap will have to be bridged partially by an increased effort in generic detector R&D, as well by encouraging and supporting Primary Investigators (PI) to get involved in other short-term, smaller scale experiments in other areas, such as astro-particle physics or accelerator-based dark matter

and rare processes experiments. The HEP community should encourage sufficient funding for small-scale experiments. An expansion into newly enabled Quantum Information Science (QIS) experiments, exploiting recent transformative technological advances should also be encouraged. In general, careers in detector instrumentation in HEP need better support. A valuable addition would be increased opportunities for interdisciplinary PhD, leveraging the Science Graduate Student Research (SCGSR) program. Furthermore, the field needs more mid-career positions for instrumentation experts, especially at Universities, where an additional advantage lies in the potential for cross-cutting positions with other departments, such as material science, quantum information, or engineering disciplines. When reviewing such mid-career and even permanent positions for primarily instrumentation physicists, a different set of metrics might have to be taken into account in order to evaluate skills, achievements and future potential.

In addition to the maintenance of the technical workforce and expertise, it is also crucial that the community invests in modern facilities, which enable breakthrough advances in detector technologies for future experiments. A coherent set of supporting facilities needs to be maintained and enhanced over the coming years. Furthermore, the US HEP community needs to consider the creation of a detector R&D collaborative framework similar or connected to the successor of the RD collaboration model at the European Center for Nuclear Research (CERN), which is consolidating detector R&D collaborations under the European Committee for Future Accelerators (ECFA). These could be in specific technological areas and under the guidance and oversight of the Coordinating Panel for Advanced Detectors (CPAD) of the American Physical Society's Division of Particles and Fields (APS/DPF).

In order to stimulate transformational breakthroughs, we need to pursue synergies with other disciplines outside of HEP, as well as close collaborations with industry. Recent successful examples of this are QIS and Microelectronics, where communication and exchange between the HEP and other communities led to enhanced funding for technology development, which together with a new suite of available or achievable detector technologies and methods opened up a new suite of small-scale experiments that enhance the HEP portfolio, and can in turn contribute new solutions to traditional experiments.

To conclude, the Snowmass science frontiers, Cosmic Frontier, Energy Frontier, Neutrino Frontier and Rare and Precision Frontier, are pursuing a breadth of different future experiments, which have aggressive schedules and are technically challenging. They urgently require significant developments within the instrumentation frontier, which in turn requires significant investment now. The key challenges can be summarized as follows:

IF-1 Advance performance limits of existing technologies and develop new techniques and materials, nurture enabling technologies for new physics, and scale new sensors and readout electronics to large, integrated systems using co-design methods.

IF-2 Develop and maintain the critical and diverse technical workforce, and enable careers for technicians, engineers and scientists across disciplines working in HEP instrumentation, at laboratories and universities.

IF-3 Double the US Detector R&D budget over the next five years, and modify existing funding models to enable R&D consortia along critical key technologies for the planned long term science projects, sustaining the support for such collaborations for the needed duration and scale.

IF-4 Expand and sustain support for blue-sky R&D, small-scale R&D, and seed funding. Establish a separate agency review process for such pathfinder R&D, independently from other research reviews.

IF-5 Develop and maintain critical facilities, centers and capabilities for the sharing of common knowledge and tools, as well as develop and maintain close connections with international technology roadmaps, other disciplines and industry.

In the following we summarize detailed findings and needs from the ten Topical Groups of the Instrumentation Frontier. Further details are given in the individual Topical Group reports.

7.1 Quantum Sensors

The use of quantum sensors in HEP has seen explosive growth since the previous Snowmass Community Study. This growth extends far beyond HEP impacting many areas of science from communications to cryptography to computing. Quantum sensors have been used in searches for dark matter - particle and wave, fifth forces, dark photons, permanent electric dipole moment (EDM), variations in fundamental constants, and gravitational waves, among others. These sensors come in a wide range of technologies: atom interferometers and atomic clocks, magnetometers, quantum calorimeters and superconducting sensors to name a few. Early work with quantum sensors in the context of particle physics often focused in cosmic and rare and precision frontiers, but recent concepts seek to expand the use of quantum sensors to the energy and neutrino frontiers solidifying them as fundamental technologies for the future of experimental HEP. Based upon input to the Snowmass process and outlined in our Topical Group report [2], our Topical Group has identified several key messages necessary to support the development and use of quantum sensors in HEP:

IF01-1 Continue strong support for a broad range of quantum sensors. Quantum sensors address scientific needs across several frontiers and different technologies carve out unique parameter spaces. While these sensors share many common characteristics, each has advantages that make it the sensor of choice for specific applications along with challenges that need further development to make the greatest impact.

IF01-2 Continue support for R&D and operation of table-top scale experiments. Many are shovel ready and have the potential for large impact. Much of the growth in quantum sensors over the past decade has occurred in small, laboratory based experiments. These fast-paced small experiments should continue to be supported as a way to rapidly develop sensor technology and help determine those areas where quantum sensors can have the greatest impact.

IF01-3 Balance support of tabletop experiments with pathfinders R&D to address the large-scale challenges of scaling up experiments which will require National Lab and HEP core competences. As the fast-paced, small experiments mature, those with significant discovery potential begin to emerge along with areas of commonality between the experiments (e.g. the need for advanced high field magnets for axion dark matter experiments or ultra-stable lasers for atom interferometers and clocks). They have reached the point at which plans for larger-scale, longer-term experiments should be conceptualized. These concepts can evaluate the potential reach that can be achieved in a larger effort and the scale of require technological development.

IF01-4 Develop mechanisms to support interactions outside of the HEP program to enable collaborations with fields with developed expertise in quantum sensors. Advances in QIS provide exceptional theoretical and experimental resources to advance quantum sensing that could provide mutual benefits in several areas such as materials, detectors, and devices. Many of the most promising quantum sensors for HEP science have been developing for the past decade or more in areas outside of the traditional HEP science and funding sphere. For example, atomic clocks developed over many decades as a source of precision timing standards are now stable enough they can be used in the search for variations of fundamental constants and gravitational waves. The HEP community should strive to collaborate with these broader communities in a way the gives

HEP access to new sensor technologies while sharing HEP expertise (e.g. large magnets and vacuum systems). Effort should be made to allow the free flow of ideas and effort across traditional funding boundaries to encourage scientists and engineers working with quantum sensors to tackle the most interesting and challenging problems available.

IF01-5 Develop mechanisms to facilitate interactions to support theoretical work address issues of materials and measurement methods. As with other instrumentation frontiers and as quantum sensors become more sensitive, focused support on quantum materials at the interface of quantum sensors and HEP will be needed. This includes theoretical work necessary for on topics including quantum materials, squeezing, and back action.

IF01-6 Workforce development is needed to encourage workers with the needed skills to engage with the HEP field, maintain current momentum, and for long-term success in the face of growing competition from industrial quantum computing. While the HEP community is poised to benefit from quantum sensor developments outside of HEP, we face a shortage of skilled workers. The explosive growth in quantum computing in recent years, along with arrival of several major tech companies has created a fierce competition for workers with skills needed to develop quantum sensors and experiments. The HEP community will need to invest now in order to train and retain the next generation of quantum scientist. Increasing collaborations outside of HEP – as discussed above – can provide an additional pathway to reaching skilled workers and engaging them on HEP challenges.

7.2 Photon Detectors

The Photon Detectors Topical Group has identified two areas where focused R&D over the next decade could have a large impact in HEP experiments. These areas described here are characterized by the convergence of a compelling scientific need and recent technological advances. A short summary can be found below, while a more extensive report, including a large number of references for further reading, is given in the Photon Detector Topical Group report [3].

The development of detectors with the capability of counting single photons from infrared (IR) to ultra-violet (UV) has been a very active area in the last decade. Demonstration for sensors based on novel semiconductor technologies such as Complementary Metal-Oxide-Semiconductor (CMOS), Charge Coupled Devices (CCD), skipper-CCDs, and Silicon Photomultiplier (SiPM) as well as superconducting technologies such as Microwave Kinetic Inductance Detectors (MKID), Superconducting Nanowire Single Photon Detectors (SNSPD) and Transition Edge Sensors (TES) have been performed. These sensors open a new window for HEP experiments in the low photon number regime. Several ongoing and future projects in HEP benefit from these developments (Cosmology, Dark Matter, Neutrinos) which will also have a large impact outside HEP such as in Basic Energy Science (BES), QIS, and Astronomy. The combined scientific needs and technological opportunities make photon counting an ideal area for focused R&D investment in the coming decade. R&D is needed for enabling large arrays of the new sensors, improving their energy resolution, timing, dark counts rates and extending their wavelength coverage. Such investment will secure leadership in photon counting technologies in the US, producing a large impact in HEP, with applications outside HEP. This opportunity is summarized in Ref [4].

A technological solution for the photon detection system in the first two modules of the DUNE detector exist, based on the by now well-known Arapuca light traps, with wavelength shifters and SiPMs as the photon detector. However, new photon detector developments are being considered for modules 3 and 4. Some of the proposed ideas consist on novel light collectors, the so-called dichroicons which are Winston-style

light concentrators made from dichroic mirrors, allowing photons to be sorted by wavelength, directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band short-wavelength scintillation light to other sensors. This technology could be used in water-based liquid scintillators thus realizing a hybrid Cherenkov and scintillator detector.

One significant development in the last decade is the commercialization of Large Area Picosecond Photodetectors (LAPPDs) and their first deployment in a neutrino experiment, ANNIE. LAPPDs are imaging single-photon sensors, capable of resolving photon hit positions with sub-cm resolution and arrival times of around 50 ps. LAPPDs bring capabilities that may make them useful in future liquid Argon (LAr) detectors, and as part of the DUNE near detector system, particularly the gaseous Argon near detector (ND-GAr). They also have the requisite time resolution to separate between early-arriving Cherenkov light and slower scintillation light.

Also notable are research and development efforts in new materials that could be directly sensitive to the vacuum ultra-violet (VUV) light, such as amorphous selenium (a-Se) and organic semiconductors. R&D is needed to move from concept demonstrations to full scale implementations in an HEP experiment. Future investment in the above technologies over the next decade will enhance the science of the DUNE project.

The science for generation, detection and manipulation of light is extremely fast moving and driven mainly from outside our field. The HEP community would benefit from resources dedicated to the implementation of these advanced photonic technologies in particle physics experiments.

IF02-1 The development of detectors with the capability of counting single photons from IR to UV has been a very active area in the last decade. We now need to pursue R&D to implement these in HEP experiments by making larger arrays, improving their energy resolution, timing, dark counts rates and extending their wavelength coverage.

IF02-2 New photon detector developments are being considered for planned future neutrino experiments going beyond the current technologies. Concept demonstrations have been done, and we now need to move from a conceptual phase to working detectors.

7.2.1 Photon Counting Sensors Enabling HEP

Several novel cosmological facilities for wide-field multi-object spectroscopy were proposed for the Astro2020 decadal review, and are being considered as part of the Snowmass process. Ground-based spectroscopic observations of faint astronomical sources in the low-signal, low-background regime are currently limited by detector readout noise. Significant gains in survey efficiency can be achieved through reductions by using sensors with readout noise below 1e-. Pushing the current photon counters in the direction of mega pixel arrays with fast frame rate (about 10 fps) would make this possible.

Dark matter searches based on photon counting technologies currently hold the world record sensitivity for low mass electron-recoil dark matter semiconductors are among the most promising detector technologies for the construction of a large multi-kg experiment for probing electron recoils from sub-GeV dark matter (DM) (skipper-CCDs). Significant R&D is needed to scale the experiments from the relatively small pathfinders to the multi-kg experiments in the future.

Single photon counting sensors have also gained importance for their potential as Coherent Elastic neutrino Nucleus Scattering (CEvNS) detectors. The deposited energy from CEvNS is less than a few keV. Only part

of this energy is converted into detectable signal in the sensor (ionization, phonons, etc.) and therefore low threshold technologies are needed. Semiconductor and superconducting technologies with eV and sub-eV energy resolution for photon counting capability in the visible and near-IR are natural candidates to reach the necessary resolution for this application.

Photon counting also enables a wide range of science outside HEP including QIS, BES and applications in radiation detection.

Recent advances in photon counting technology are discussed here. The advances can be grouped in three areas.

7.2.1.1 Superconducting Sensors

MKIDs work on the principle that incident photons change the surface impedance of a superconductor through the kinetic inductance effect. The magnitude of the change in surface impedance is proportional to the amount of energy deposited in the superconductor, allowing for single photon spectroscopy on chip. Frequency multiplexed arrays of 20,440 pixels with energy resolution R=E/ΔE$\sim$9.5 at 980 nm, and a quantum efficiency (QE) of $\sim$35% have been achieved. R&D focused on larger arrays with higher QE and better energy resolution would address the needs of the community.

TES is a photon detector, which utilizes a patterned superconducting film with a sharp superconducting-to-resistive transition profile as a thermometer. It is a thermal detector with a well developed theoretical understanding. When a visible or infrared photon is absorbed by a TES, the tiny electromagnetic (EM) energy of the photon increases the temperature of the TES and therefore changes its resistance. TES have been developed to measure single photons in quantum communication, for axion-like particle searches, direct detection of dark matter particles and astrophysical observations in the wavelengths between UV and IR. TES detectors can be multiplexed enabling arrays of large channel counts. Multiplexers for detector arrays using 16,000 TES have already been successfully implemented. R&D exploiting microwave resonance techniques has the potential to increase the multiplexing capacity by another factor of ten.

SNSPDs consist of a superconducting film patterned into a wire with nanometer scale dimensions (although recently devices with micrometer-scale widths have been shown to be single-photon sensitive). SNSPDs have been reported with single photon sensitivity for wavelengths out to several microns, timing jitter as low as a few ps, dark count rates down to 6×10^{-6} Hz, and detection efficiency of 0.98. They have also been shown to function in magnetic fields of up to 6T. Current R&D consist on scaling to large arrays and extending the spectral range for these sensors to address the needs of HEP and Astrophysics.

7.2.1.2 Semiconducting Sensors

Skipper-CCDs have an output readout stage that allows multiple non-destructive sampling of the charge packet in each pixel of the array thanks to its floating gate output sense node. This non-destructive readout has been used to achieve deep sub-electron noise in mega-pixel arrays. Skipper-CCDs fabricated on high resistivity silicon have also demonstrated an extremely low production of dark counts. This technology has motivated a new generation of DM and neutrino experiments. The R&D effort here is currently focused on faster readout (10 fps) and large gigapixel arrays.

CMOS The down scaling of CMOS technology has allowed the implementation of pixels with a very low capacitance, and therefore, high sensitivity and low noise (1-2 e^-) at room temperature and high frame rates (50-100 fps). Commercial cameras with sub-electron noise at 5 fps are now available. These sensors have not yet played a big role in HEP mainly because of the small pixel size. Active R&D taking advantage of the CMOS fabrication process to address the needs of HEP is ongoing, including the development of new CMOS sensors with non-destructive readout (skipper-CMOS). These sensors could address the readout speed limitations of other semiconductor photon counters. The single photon avalanche diode (SPADs) have also been implemented in standard CMOS technology and integrated with on-chip quenching and recharge circuitry addressing fast timing and radiation tolerance requirements from HEP.

Photon-to-Digital Converters (PDC) In a PDC, each SPAD is coupled to its own electronic quenching circuit. This one-to-one coupling provides control on individual SPADs and signals each detected avalanche as a digital signal to a signal processing unit within the PDC. Hence, PDCs provide a direct photon to digital conversion considering that intrinsically a SPAD is a Boolean detector by design. Digital SiPMs were first reported in 1998 by the MIT Lincoln Lab (MIT-LL) and many contributions followed. A major step came with microelectronics integration to fabricate both the SPAD and readout quenching circuit in a single commercial process. These innovations led to the first multi-pixel digitally read SPAD arrays. A recent review can be found in Ref. [5].

7.2.1.3 Extending Wave Length Coverage

As has been pointed out also in [6], Sec.3.3.3, low-gap materials are being developed which could also serve as THz-IR single photon detectors.

Germanium Semiconductors Silicon CCDs are commonly utilized for scientific imaging applications in the visible and near infrared. These devices offer numerous advantages described previously, while the skipper-CCD adds to these capabilities by enabling multiple samples during readout to reduce read noise to negligible levels. CCDs built on bulk germanium offer all of the advantages of Silicon CCDs while covering an even broader spectral range. The R&D in this area will extend the photon counting capabilities of semiconductor into the IR.

UV It has been shown that CCD sensitivity can be increased close to the reflection-limited quantum efficiency of silicon. This was done by blocking the surface fields and traps through the epitaxial growth of a strongly doped very thin silicon layer (delta-doping). QE exceeding 50% was demonstrated in CCDs down to 125 nm wavelength. The method was demonstrated efficiently on backside-illuminated SPAD-based detectors. Other methods to address the surface field and trap issues were also demonstrated. Work is being done to enhance SiPMs for the detection of the fast scintillation component of Barium Fluoride (BaF_2). An extensive study of the delta-doping approach to enhance VUV sensitivity in frontside-illuminated SPAD-based detectors has also been carried out.

7.2.2 Photon Detectors For Neutrino Experiments

A large number of outstanding questions remain to the fundamental nature of the neutrino, which can be probed through the use of higher energy ($\mathcal{O}(\text{MeV}) < E < \mathcal{O}(\text{GeV})$) neutrino sources (*e.g.*, accelerator

and atmospheric neutrinos). The nature of these remaining puzzles break into the distance over which the neutrinos are allowed to propagate before being detected. Thus the future class of experiments are classified as "short-baseline" and "long-baseline" experiments.

The next generation long-baseline neutrino experiments aim to answer the questions of the exact ordering of the neutrino mass states, known as the mass hierarchy, as well as the size of the CP-violating phase δ. These, as yet unknown quantities, remain one of the last major pieces of the Standard Model of particle physics and offer the opportunity to answer such fundamental questions as "what is the origin of the matter/antimatter asymmetry in the universe?" and "do we understand the fundamental symmetries of the universe?". By measuring the asymmetry between appearance of electron neutrinos from a beam of muon neutrinos ($P(\nu_\mu \rightarrow \nu_e)$) compared to the appearance of electron antineutrinos from a beam of muon antineutrinos and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$) as well as the precise measurement of the ν_e energy spectrum measured at the far detector, both the CP violating phase (δ_{CP}) and the mass hierarchy can be measured in the same experiment.

The Short-Baseline Neutrino (SBN) program aims to address the anomalous neutrino results seen by the Liquid Scintillator Neutrino Detector (LSND) and MiniBooNE experiments, which suggest the possible existence of an eV mass-scale sterile neutrino. However, the experimental landscape is perplexing since a number of other experiments utilizing a range of different neutrino sources which should have been sensitive to such a sterile neutrino have observed only the standard three neutrino oscillations. In this landscape, the conclusive assessment of the experimental hints of sterile neutrinos becomes a very high priority for the field of neutrino physics.

To address both of these areas of neutrino research, large scale noble element time projection chambers (TPC) play a central role and offer an opportunity to perform discovery level measurements through the enhancement of their capabilities. In a noble element TPC, particles interact with the medium and deposit their energy into three main channels: heat, ionization, and scintillation light. Depending on the physics of interest, noble element detectors attempt to exploit one or more of these signal components. Liquid Noble TPCs produce ionization electrons and scintillation photons as charged particles traverse the bulk material. An external electric field allows the ionization electrons to drift towards the anode of the detector and be collected on charge sensitive readout or transform energy carried by the charge into a secondary pulse of scintillation light.

A technological solution for the photon detection system in the first two modules of the DUNE detector exist, based on the Arapuca light traps, with wavelength shifters and SiPMs as the photon detector. This approach is also being used in other SBN oscillation experiments, but not exclusively. Beyond this, new photon detector developments are being considered for DUNE modules 3 and 4 as well as for other approved or proposed experiments.

7.2.2.1 Going Beyond DUNE's First Two Modules

Quoting from the executive summary of the Snowmass IF02 White Paper *Future Advances in Photon-Based Neutrino Detectors* [7], large-scale, monolithic detectors that use either Cherenkov or scintillation light have played major roles in nearly every discovery of neutrino oscillation phenomena or observation of astrophysical neutrinos. New detectors at even larger scales are being built right now, including Jiangmen Underground Neutrino Observatory (JUNO), Hyper-Kamiokande (Hyper-K), and DUNE. These new technologies will lead to neutrino physics and astrophysics programs of great breadth: from high-precision accelerator neutrino oscillation measurements, to detection of reactor and solar neutrinos, and even to neutrinoless double beta decay measurements that will probe the normal hierarchy regime. They will also be valuable for neutrino applications, such as non-proliferation via reactor monitoring.

Of particular community interest is the development of hybrid Cherenkov-scintillation detectors, which can simultaneously exploit the advantages of Cherenkov light's reconstruction of direction and related high-energy particle identification (PID) and the advantages of scintillation light, high light-yield, low-threshold detection with low-energy PID. Hybrid Cherenkov-scintillation detectors could have an exceptionally broad dynamic range in a single experiment, allowing them to have both high-energy, accelerator-based sensitivity while also achieving a broad low-energy neutrino physics and astrophysics program. Recently the Borexino Collaboration has published results showing that even in a detector with standard scintillator and no special photon sensing or collecting, Cherenkov and scintillation light can be discriminated well enough on a statistical basis that a sub-MeV solar neutrino direction peak can be seen. Thus the era of hybrid detectors has begun, and many of the enabling technologies described here will make full event-by-event direction reconstruction in such detectors possible.

LAPPDs New advances in the science of photomultiplier tubes, including long-wavelength sensitivity, and significant improvements in timing even with devices as large as 8 inches, make hybrid Cherenkov-scintillation detectors even better, with high light yields for both Cherenkov and scintillation light with good separation between the two types of light. LAPPDs have pushed photon timing into the picosecond regime, allowing Cherenkov-scintillation separation to be done even with standard scintillation time profiles. The fast timing of LAPPDs also makes reconstruction of event detailed enough to track particles with the produced photons. The precision timing capabilities of LAPPDs make possible new stroboscopic techniques where different energy components of a wide-band neutrino beam can be selected based on the arrival of the neutrinos relative to the beam Radio Frequency (RF) timing. Future neutrino experiments, including possible upgrades to the Long Baseline Neutrino Facility (LBNF), could enable sufficiently short proton bunches to make this technique viable. At the detector end, this technique requires time resolutions on the order of no more than a few hundred picoseconds. Hybrid Cherenkov-scintillation detectors with LAPPDs are naturally well suited for this level of vertex precision. The continued use and development of application readiness of LAPPDs in experiments like ANNIE is critical to their future viability. Additional investments in R&D to further grow production yields and reduce costs will also benefit future large-scale HEP efforts.

Dichroicons Dichroicons, which are Winston-style light concentrators made from dichroic mirrors. Winston cones are non-imaging light concentrators intended to funnel all wavelengths passing through the entrance aperture out through the exit aperture. In turn, a dichroicon allows photons to be sorted by wavelength thus directing the long-wavelength end of broad-band Cherenkov light to photon sensors that have good sensitivity to those wavelengths, while directing narrow-band short-wavelength scintillation light to other sensors. Dichroicons are particularly useful in high-coverage hybrid Cherenkov-scintillation detectors.

7.3 Solid State Detectors and Tracking

Tracking detectors are of vital importance for collider-based HEP experiments. The primary purpose of tracking detectors is the precise reconstruction of charged particle trajectories and the reconstruction of secondary vertices. The performance requirements from the community posed by the future collider experiments require an evolution of tracking systems, necessitating the development of new techniques, materials and technologies in order to fully exploit their physics potential.

Technological developments currently underway aim to address these issues, and the successful completion of the programs outlined below requires focused efforts from the community on the steady development and

refinement of existing technologies, and the pursuit of novel blue-sky technologies to enable transformative progress. The HEP community gathered at Seattle Snowmass Summer Meeting in 2022 identified the following key directions for the near-term priorities of the solid-state tracking. The full report of this Topical Group can be found in [8].

IF03-1 Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments

IF03-2 Adapt new materials and fabrication/integration techniques for particle tracking in harsh environments, including sensors, support structures and cooling

IF03-3 Realize scalable, irreducible-mass trackers in extreme conditions

IF03-4 Push advanced modeling for simulation tools, developing required extensions for new devices, to drive device design.

IF03-5 Provide training and retain expert workforce to enable future tracking systems to be designed, developed, constructed and simulated.

IF03-6 Nurture collaborative networks, provide technology benchmarks and roadmaps and funding in order to develop required technologies on necessary time scales, costs and scope.

Advanced 4-dimensional (4D) trackers with ultra-fast timing (10-30 ps) and extreme spatial resolution (O(few μm)) represent a new avenue in the development of silicon trackers, enabling a variety of physics studies which would remain out of experimental reach with the existing technologies. Several technology solutions are being currently pursued by the community to address the challenges posed by various experiments [9–11], both for the sensors [12] and the associated electronics. The packaging and integration of the sensors and readout electronics will become more critical for future experiments, as device segmentation decreases to mitigate the increased track density. Bump bonding technologies have nearly reached their limits; more advanced 3D-packing technologies including wafer-to-wafer and die-to-wafer hybrid bonding and through silicon vias (TSV) have the potential to meet the goals of future particle physics experiments [13,14].

Detector mechanics will also play a significant role in future detectors' performance. Material necessary for cooling and structural stability will be the lower bound on the radiation length for future tracking systems. Increased segmentation will lead naturally to larger power densities; in order to minimize material, solutions with integrated services and cooling are necessary. A holistic approach to design, simulation and manufacturing will be required. Novel materials, new cooling and composite manufacturing technique will need to be developed in order to reach the targeted performance [15].

To develop these new technologies, simulations of the properties of silicon and novel sensor materials throughout the lifetime of the experiments will be critical. These studies can drive device design included implant locations, size and strength to the most promising directions of development [16]. To reach their full potential, further developments are needed to improve accuracy, precision and new devices. With this research, the performance of future experiments can be better predicted for its full life cycle prior to construction.

7.3.1 Simulations of Silicon Radiation Detectors for HEP Experiments

There are currently a variety of tools available for simulating the properties of silicon sensors before and after irradiation. These tools include finite element methods for device properties, dedicated annealing

models, and testbeam and full detector system models. No one model can describe all of the necessary physics. Most of these models are either fully or partially developed by HEP scientists and while there are many open-source tools, the most precise device property simulations rely on expensive, proprietary software.

While existing approaches are able to describe many aspects of signal formation in silicon devices, even after irradiation and annealing, there is significant R&D required to improve the accuracy and precision of these models and to be able to handle new devices (e.g. for timing) and the extreme fluences of future colliders. The US particle physics community can play a key role in this critical R&D program, but it will require resources for training, software, testbeam, and personnel.

For example, there is a great need for (i) a unified microscopic model of sensor charge collection, radiation damage, and annealing (no model can currently do all three), (ii) radiation damage models (for leakage current, depletion voltage, charge collection) with uncertainties (and a database of such models), and (iii) a measurement program to determine damage factors and uncertainties for particle types and energies relevant for current and future colliders. Equipped with these tools, the US community can play a key role in the success of future collider physics, and help in defining the most promising avenues to realize the necessary performance of future experiments.

7.3.2 Novel Sensors for Particle Tracking

The proposed future collider experiments pose unprecedented challenges for event reconstruction, which require development of new approaches in detector designs. Several technologies are currently being investigated to develop technologies for the future, which approach these goals in complementary ways.

Silicon or diamond sensors with 3D-technology have electrodes oriented perpendicular to the plane of the sensor. New 3D-geometries involving p-type trench electrodes spanning the entire thickness of the detector, separated by lines of segmented n-type electrodes for readout, promise improved uniformity, timing resolution, and radiation resistance. Present research aims for operation with adequate signal-to-noise ratio at fluences approaching 10^{18} $n_{\mathrm{eq}}/\mathrm{cm}^2$, with timing resolution on the order of 10 ps.

Monolithic Active Pixel Sensors (MAPS), in which charge collection and readout circuitry are combined in the same pixel, have been shown to be a promising technology for high-granularity and low material budget detector systems. MAPS have several advantages over traditional hybrid pixel detector technologies, as they can be inexpensively fabricated in standard CMOS imaging processes, back-thinned or back-illuminated, have demonstrated high radiation hardness. Many MAPS pixel geometries have been explored, but the close connection of a sensor and front-end amplifier, without the need for external interconnections, holds the promise of reducing the input capacitance significantly, and hence extremely low-noise designs are possible. The reduction of the noise floor means that even small signals, for example from thinned low-power sensors, can yield satisfactorily high signal-to-noise.

The DoTPiX pixel architecture has been proposed on the principle of a single n-channel Metal-Oxide Semiconductor (MOS) transistor, in which a buried quantum well gate performs two functions: as a hole-collecting electrode and as a channel current modulation gate. The quantum well gate is made with a germanium silicon substrate. The active layers are of the order of 5 μm below the surface, permitting detection of minimum ionizing particles. This technology is intended to achieve extremely small pitch size to enable trigger-free operation without multiple hits in a future linear collider, as well as simplified reconstruction of tracks with low transverse momentum near the interaction point.

Furthermore, a technology is under development in which a novel ultra-fast scintillating material employs a semiconductor stopping medium with embedded quantum dots. The candidate material, demonstrating very high light yield and fast emission, is a gallium arsenide (GaAs) matrix with indium arsenide (InAs) quantum dots. The first prototype detectors have been produced, and pending research goals include demonstration of detection performance with minimum ionizing particles, corresponding to signals of about 4000 electron-hole pairs in a detector of 20 μm thickness. A compatible electronics solution must also be developed. While the radiation tolerance of the device is not yet known, generally quantum dot media are among the most radiation hard semiconductor materials.

Thin film detectors have the potential to be fully integrated, while achieving large area coverage and low power consumption with low dead material and low cost. Thin film transistor technology uses crystalline growth techniques to layer materials, such that monolithic detectors may be fabricated by combining layers of thin film detection material with layers of amplification electronics using vertical integration.

7.3.3 4-Dimensional Trackers

Future collider experiments call for development of tracking detectors with 10-30 ps timing resolution, in addition to excellent position resolution, i.e. 4D-trackers. Time resolution of the future 4D-tracker detector can be factorized into contributions from the sensor itself, and those from the readout electronics. The overall detector system should contain a sensor with short drift time, high signal to noise, limited thickness in the path of a minimum ionizing particle (MIP) to reduce the Landau fluctuations, and small time-to-digital converter (TDC) bin size. Several technologies to address these needs are being developed and are introduced in this section.

Several modifications to Low Gain Avalanche Detectors (LGADs) technology have been proposed and demonstrated to make them suitable for tracking sensors with 100% fill-factor, achieving excellent timing and position resolution. A key feature of analog-coupled "AC-LGADs" is the signal sharing between electrodes, which can be used to obtain the simultaneous 30 ps and 5 μm resolutions. Another design geared towards 100% fill factor are the "Deep-Junction" (DJ-LGAD), which are formed by abutting thin, highly-doped p+ and n+ layers. "Buried Layer LGADs" aim to achieve higher radiation tolerance by implanting the boron layer at low energy, and then burying it under a few microns of epitaxially grown silicon.

Another thrust to develop 4D-tracking sensors is through a usage of novel sensors with 3D-geometries, or closer integration with electronics via monolithic pixel sensors, or adoption of new materials in sensor design. Going even beyond 4D-sensors are designs that aim to simultaneously measure not only the position and time, but also the angle of passing tracks. These kind of sensors would dramatically reduce the complexity of detector modules, and enable unprecedented reconstruction capabilities on the front-end. "Double Sided LGADs" (DS-LGADs) achieve this goals by adding a readout layer to the p-side of the LGAD structure, which allows one to also measure signals from the slower-drifting holes.

The timing Application Specific Integrated Circuits (ASICs) under development for the HL-LHC timing upgrades, named ALTIROC (ATLAS) and ETROC (CMS), represent revolutionary steps forward as the first readout chips to bring O(10 ps) timing to collider experiments. However, they are able to use significantly more space and power than high density ASICs designed for trackers with fine pitch and limited material. Compared to the RD53A ASIC designed for the HL-LHC pixel tracker upgrades, the timing chips use several hundred times more power and area per channel. The primary challenges to transform them into chips for 4D-tracking will be to minimize both the power consumption and the channel size. Currently there are several projects with the aim to make advances in these areas.

7.3.4 Integration

In the past years, HEP experiments have been mostly relying on bump bonding for high-density pixel sensor-to-ASIC connection. The bump bonding technology was proven to be reliable; however, it is known to have several limitations: it only works down to 20-50 μm of pitch and has yield issues for finer connections. Furthermore, the solder balls used for the connection increase the input capacitance to the amplifier and hence the noise. With bump bonding,the sensor or chip need side extensions to have external connections. In terms of mechanical properties the resulting connection is subject to heat stress since it involves different materials; the minimum thickness is also limited since both chip and sensor need a thick enough support wafers in order to meet alignment and bow requirements for the bump bonding process.

The introduction of more advanced packaging can solve many of these issues, allowing for the improvement of performance, yield and processing. 3D-integration is a common widespread technology in industry, it allows tight packaging of sensor and readout chip. Furthermore it allows to stacks multiple chips in a single monolithic device. There are many technologies available for 3D-integration, hybrid bonding is the most widely accepted. TSVs allow multiple planes to be stacked and connected with external connections without the need of extensions or silicon interposers.

Advanced packaging and wafer to wafer bonding would facilitate several applications both in HEP and outside of HEP. Therefore, electronics and sensor advanced packaging provide a variety of technologies that can meet the needs of future particle physics experiments. Combining these capabilities with silicon technologies developed for HEP, such as LGADs and active edge sensors, will allow the design of sophisticated detector systems that can meet the increasing challenges of next generation experiments. The collaboration between research groups and industry with established expertise in advanced packaging is crucial for the successful introduction of this technology in the research community.

Current availability of such technologies is mixed. Leading edge foundries and nodes now include 3D-processes (Intel Forveros, TSMC 3DFabric, Samsung x-cube) but are typically too expensive for HEP. Hybrid bonding is available from many vendors that already work with HEP. The availability of TSVs is more limited. Small pitch TSVs are available from some foundries at advanced nodes (>32 nm), in Silicon-on-Insulator (SOI) wafers, and from specialty foundries. Larger pitch TSVs inserted in a completed wafer (via-last) are available from a variety of packaging suppliers. Reliable 3D-devices with these large pitch (>20 μm) external TSV connections can be accessed now with resources available to HEP. It is important to build design and fabrication experience with moderate scale companies now gearing up to address opportunities afforded by the US semiconductor initiative.

7.3.5 Mechanics

Detector mechanics will play a significant role in future detectors' performance; the necessary improvements will require simulations, novel ways to reduce the total mass, as well as more integrated design concepts to save on material budgets and optimize performance. The increased segmentation has naturally lead to larger power densities requiring high performance material support structures with integrated services. In many cases, the material in these structures can be the limiting factor for the tracking performance of the system. Particle detectors at future colliders rely on ever more precise charged particle tracking devices, which are supported by structures manufactured from composite materials. Various engineering techniques able to solve challenges related to the design and manufacturing of future support structures have been developed.

Future particle colliders, such as the HL-LHC, the Future Circular Collider (FCC-ee, FCC-hh), or a muon collider will collide particles at unprecedented rates and present a harsh environment for future detectors. A holistic approach to the design and manufacturing of detector support structures will be necessary to achieve minimal weight systems. Novel techniques, materials and other design and manufacturing solutions provide an avenue to solve challenges of increasingly more complex and large tracking detectors. Complex stresses in composite structures pose a severe challenge to current simulation tools. Research and development efforts are underway to solve these challenges by exploring multi-functional composite structures.

Material savings due to novel approaches have the potential of reduction on the order of 30-50% depending on more detailed R&D studies. This is an ideal opportunity to explore the conjunction of latest techniques in composite engineering involving machine learning based algorithms for heat transfer, mechanical loading and micro-to-macro scale material response predictions. Different structures are being studied to achieve these goals which include: carbon fiber support structures with integrated titanium pipes for CO_2 cooling, etched silicon and peak cooling micro-channels, Kapton-based support structures and engineered air cooling.

7.3.6 Collaborative Development Programs

Collaborative efforts should be encouraged when possible to make efficient use of resources and reduce the financial burden on individual groups, and to enlarge the pool of expertise in the field. Especially critical is to encourage and support young researchers to engage and pursue intensive research programs to develop these new technologies, which will help to ensure an expert workforce is sustained for the long term. Considering the prohibitively high costs for productions of new technologies at commercial foundries, collaborative submissions can provide the only viable solution for research groups to access advanced production facilities. Such collaborations promise to significantly expand the possibilities for small experiments or small groups to join advanced detector R&D programs, work with others in the field to build technology demonstrators, and help advance the solid-state tracking technology.

7.4 Trigger and Data Acquisition (DAQ)

A trend for future HEP experiments is an increase in the data bandwidth produced from the detectors. Datasets of the Petabyte scale have already become the norm, and the requirements of future experiments – greater in size, exposure, and complexity – will further push the limits of data acquisition technologies to data rates of exabytes per seconds. The challenge for these future data-intensive physics facilities lies in the reduction of the flow of data through a combination of sophisticated event selection in the form of high-performance triggers and improved data representation through compression and calculation of high-level quantities. These tasks must be performed with low-latency (*i.e.* in real-time) and often in extreme environments including high radiation, high magnetic fields, and cryogenic temperatures. The Snowmass Instrumentation Frontier Topical Group discussions have been summarized in [17].

Developing the trigger and data acquisition (TDAQ) systems needed by future experiments will rely on innovations in key areas:

IF04-1 Pursue innovations in the application of Machine Learning (ML) to TDAQ systems, particularly in the co-design of hardware and software to apply ML algorithms to real-time hardware and in other novel uses to improve the operational efficiency and sensitivity to new physics of future experiments;

IF04-2 Invest in the design of TDAQ system architectures that leverage new technologies, techniques, and partnerships to enable more intelligent aggregation, reduction, and streaming of data from detectors to higher-level trigger systems and offline data processing; and,

IF04-3 Develop improved readout technologies that increase data bandwidth and are capable of operating in extreme environments, while fitting the material and power constraints of future experiments.

Critically, innovations in TDAQ rely on the people and processes behind them, and require investments in those people and infrastructure for R&D. To that end, we call for:

IF04-4 Increased effort to build and retain domain knowledge for complex TDAQ systems by reliably supporting facilities and people – particularly engineers and technical staff, and early-career scientists through recruitment and training – in order to bring new ideas from early design and prototyping all the way through integration, commissioning, and operation in future detectors; and,

IF04-5 The creation of a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offer opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and develop and maintain an accessible knowledge-base that crosses experiment-project boundaries.

7.4.1 A Compelling Use Case: Track-based Triggers

Searches for novel new physics are often made possible by the development of novel new triggers that take advantage of improvements in detectors and real-time computing. Early-stage trigger systems of experiments at hadron collider experiments, for example those at the Large Hadron Collider (LHC [18]), often select objects with high momentum, based on calorimeter information, in order to reduce the large backgrounds to events of physical interest. However, this process necessarily loses many events, and is poorly optimized to explore a variety of potential beyond Standard Model (SM) scenarios. For instance, low momentum events with displaced vertices could lead to soft-unclustered-energy-patterns, long-lived staus or the decays of long-lived dark scalars in the Higgs portal scenario [19]. Alternatively, high-momentum and short-lived particles, such as particle dark matter, might be missed by the existing trigger systems due to their invisible decay within the detector volume [20].

For both of these cases, early-stage triggers based on tracking information could preserve interesting signal events for study. A difficulty of including tracking information in early-stage triggers is the complexity of calculating tracks and the speed at which decisions need to be made. For instance, at the LHC events are produced at a rate of 40 MHz, and this must be very rapidly reduced to the kHz level at the first step of the trigger system. The development of a fast track-based trigger is therefore an area of considerable interest in the HEP community, and several different approaches have been taken to solve the problem for silicon-strip tracking systems. For future hadron collider experiments, a fast tracking trigger for silicon pixel tracking layers at small radii with respect to the beam pipe, and therefore with significantly more channels than strip trackers, would open the sensitivity to particles arising from beyond SM physics in an interesting lifetime regime.

As a new approach, a white paper contributed to Snowmass [20] utilizes highly-parallelized graph computing architecture using field-programmable gate arrays (FPGAs) to quickly performing tracking in small-radius silicon detectors. This paper proposes unsupervised machine learning on a highly-parallelized graph computer constructed using modern FPGA technology. As documented in [21], this algorithm yields a

trigger efficiency near 100% for track transverse momenta above 10 GeV and a spurious trigger rate of a few kHz. Implementation studies on a Virtex Ultrascale+ FPGA are in progress and indicate a latency of 200 ns, well below the 4 μs limit for trigger algorithms at LHC experiments.

We note that the design of future detector systems, especially tracking systems in dense, high occupancy environments, is best done taking into account the necessary trigger and DAQ considerations early in the process. For example, the design of the HL-LHC silicon tracker for the CMS experiment [22] utilizes the local coincidence of hits in two closely-spaced tracking layers to provide some limited momentum selection capability. This is necessary to reduce the data rate from the detector to manageable levels for the early-level trigger system.

7.4.2 Heterogeneous Computing and Machine Learning

As is well known, the scaling of single Central Processing Unit (CPU) solutions to efficiently address computational problems has reached its limits, and the need for the parallelization of tasks across many CPU cores, in Graphical Processing Units (GPUs), or in other specialized hardware like FPGAs and ASICs has become necessary. The choice of technology often depends on the timescale and amount of data to handle. For high-energy physics experiments this means moving beyond the natural parallelization of processing individual data "events" (e.g. beam crossings, which are independent of each other) to the parallelization of the algorithms themselves acting upon the data of single event. This requires a new paradigm of coding algorithms to take advantage of the available heterogeneous computing hardware, and thus utilizing industry tools or developing domain specific tools to aid in this parallelization.

ML algorithms lend themselves well to be distributed on such heterogeneous computing platforms using standard libraries, and thus make a natural and powerful target for trigger applications. The applications include the very specialized and local processing at the front-end of the detector electronics ("edge" computing) where low-level detector hits are converted into clusters or other higher-level data objects at high frequency and low latency, but also the more global and generalized processing needed to discriminate physics signatures from backgrounds. ML also could potentially be used to go beyond the fixed hand-curated trigger menus used to select physics data at colliders to a novel "self-driving" paradigm whereby the trigger system autonomously and continuously learns from the data to more efficiently and effectively filters and selects data from a detector system, as discussed in white paper [23]. Such systems may complement dedicated triggers, searching for specific signatures of Beyond-Standard-Model physics, by performing a general set of anomaly detection that may be sensitive to a wider variety of new physics.

Development of ML algorithms for use in the trigger and data acquisition systems of future HEP experiments is particularly challenging [24]. For example, while ML-based algorithms have proven effective at performing data reduction, through both advanced data selection and data compression, to be used in high-luminosity environments of future particle colliders these algorithms must be capable of running in on-detector electronics with latencies on the order of nanoseconds. Future neutrino, DM, and astrophysics experiments require latencies on the order of microseconds to milliseconds, and often similarly extreme detector environments.

The design and development of low-latency artificial intelligence (AI) algorithms requires optimization across both physics (*e.g.* selection efficiency, background rejection) and technical performance (*e.g.* latency, resource usage). It's necessary to consider a co-design of hardware and software that gives special attention to the processor element, making use of tools and expertise that can bring a variety of ML algorithms built on large datasets into FPGA and ASIC firmware. Open-source frameworks like `hls4ml` [25] and FINN [26] aim to ease the complexity of firmware programming, which have opened up development and integration

of sophisticated AI into high-performance hardware. Continued development of ML frameworks that can aid hardware-software co-design, coupled with (and in many cases driving) improvements in the underlying processor technologies, can open the door to paradigm shift in how future experiments will collect, reduce, and process data.

7.4.3 Innovative Architectures

For experiments where a processing element of the trigger system must have a complete view of the data from all detectors to perform its function, scalability of the trigger system can be achieved by time multiplexing the data to individual processors. This is natural for software-based trigger levels (CPUs, GPUs) in collider experiments, where data are aggregated in an event builder and sent to a target compute node for processing asynchronously. For a hardware-based synchronous trigger level (FPGAs, ASICs), this can be achieved by sending data from all detector elements for a given time slice (or event) via links to target processors in a round-robin fashion ("time multiplexing"). This will be necessary for the CRES tritium beta decay experiment, for example, where each compute node must process the data from all receivers in a given time slice.

In collider experiments, trigger data processing in the hardware-based level is still generally synchronous to the accelerator clock, even if the processing is time multiplexed. At all stages the data are processed and registered at a multiple of this frequency in the digital pipeline, and the event number is implicit by the clock (or accelerator bunch) counter. However, it is enough to time-stamp data at the very front end of the detectors with the system clock, and transmit and process the data asynchronously as traditionally done at the software-based level [27]. Effectively the event builder infrastructure moves to the first level of the trigger system. This would alleviate the challenge of distributing and synchronizing a stable, low-jitter, high frequency clock over the entirety of a very large and distributed electronics system. It also has the additional benefit of blurring the lines between the first level trigger, which typically runs in fast FPGAs, with the software-based higher levels. Another avenue of potential interest in this area is to make use of neuromorphic computing, i.e. the use of very-large-scale integration systems containing electronic analog circuits to mimic neuro-biological architectures present in the nervous system, directly on analog signals.

Another innovative approach to solving the data reduction problem for trigger and data acquisition systems is to move away from a pipelined and triggered readout, and instead operate in a more "streaming" design, where data is encoded with its time and origin [23]. In this model, pioneered by the LHCb experiment for its upgrade but being adopted to some degree as well by the other LHC experiments, event data can be reduced at its source, often through simple thresholding and zero suppression, and then aggregated and streamed to downstream computational and storage elements. There, full- or partial-event filtering and further processing and translation of data into higher-level quantities can be performed in order to achieve the reduction in the data throughput and offline computing. Hybrid designs that combine both traditional trigger-based DAQ for some detector subsystems and streaming-readout for others is also possible. Emphasis on such approaches for upgrades and experiments at future facilities has merit, especially due to its ability to simplify DAQ design.

7.4.4 Developments in Novel Readout Technologies

The needs of future detectors continue to push readout, triggering, and data acquisition technologies to operate with growing data rates in more extreme environments. Future kton-scale neutrino and dark matter

experiments like DUNE and LZ will produce many petabytes of data per year with intrinsic data rates in excess of TB/s, and require readout systems that can reliably operate in cryogenic temperatures over the long lifetimes of the experiments and minimize radiological material volumes to maintain sensitivity to low-energy interactions. In high-energy collider physics at the HL-LHC or potential future colliders like the FCC-hh, data rates in the hundreds of TB/s are possible from tracking and calorimetry systems, and must be able to withstand high radiation rates and not significantly add to the material budget of the detectors. The fundamental challenge of how to move data from readout electronics to online and offline computing resources requires a commitment to research and development in new and improved technologies.

Core to improvements in DAQ are a combination of reducing the data rate close to the detector, and increasing the data bandwidth for a given material and/or power cost, in the extreme environments required. More sophisticated data reduction techniques in detector electronics may be possible with advances in AI, particularly with improvements in translating low-latency machine-learning-developed compression and triggering algorithms to ASICs [24]. In many cases, like in fast tracking algorithms, correlations across different portions of the detector are necessary to develop effective trigger algorithms, and thus fast, localized, and low-material communication is necessary. Wireless communication technologies are an area of large promise here: microwave-based technologies already show reliable data transmission at the 5 Gb/s scale, and promising future work using free space optics may allow for wireless communication at the Tb/s scale [28]. Integration of wireless communication into HEP detector design (like, for future tracking detectors in colliders), could allow for new system designs that exploit localized readout, fast analysis, and triggering to intelligently reduce data volumes.

Technologies to allow greater bandwidth off of the detector also show significant promise [28, 29]. Silicon-photonics are an appealing alternative to the current Vertical Cavity Surface-Emitting Laser (VCSEL)-based approaches: they can allow integration of fiber-optic connections directly to sensor modules or readout chips (thus reducing the need for electrical cable connections), commercial devices already show high radiation tolerance, and offer a bandwidth twice that of VCSEL devices with a power consumption that is 20% less. More promising developments exist in Wavelength Division Multiplexing (WDM), where individual serial links can be transmitted on its own wavelength, reducing the need for data aggregation to maintain high data bandwidth per link. WDM could be used in a design to bring data out of the most extreme radiation environments in colliders more efficiently, allowing for further data reduction in downstream DAQ components.

Notably, the work to develop new readout technologies is often less in design, but more in integration and testing with real detector components in real detector environments. It is important to develop and maintain tools and facilities that can allow for realistic full-system testing of readout electronics and DAQ.

7.4.5 Timing

Time measurements will feature prominently in the next generation of particle physics experiments and upgrades, including integration into 4D-tracking systems and 5D-calorimeters (see 7.6.1). Timing helps disentangle the effects of particle pile-up in hadron collisions, discriminates against beam-induced backgrounds in a muon collider experiment, and can be used to separate Cherenkov and scintillation light signals in neutrino and dark matter experiments. Timing also provides particle ID information useful for a broad range of experiments, including sensitivity to any slow beyond-standard-model long-lived particles. Thus it seems evident that timing information will work its way into the trigger processing chain to improve its selectivity and precision of measurements. A particular challenge is the need for synchronization of data at the $\mathcal{O}(10)$ ps level or better, including across large distances in the case of RF arrays.

7.4.6 Fostering and Retaining Expertise in TDAQ

Along with the importance in conducting the R&D to develop and ultimately construct innovative trigger and data acquisition systems for future physics facilities, equally important is to build and retain the domain knowledge and technical expertise within the high-energy physics community required to support this [23]. It can be challenging to recruit and retain highly skilled personnel to address the specialized and high-tech needs of our community. Essential technical staff can leave for higher-paying positions in industry, and younger scientists specializing in instrumentation may find career progression and promotion a challenge in this field. This is compounded by the timescale for large experiment facilities from construction through to the end of operations, which can be decades. Thus it is imperative for the scientific community to provide career opportunities for such highly skilled people.

To facilitate fast machine learning development, it is very important to foster interdisciplinary collaboration between electrical engineering, computer science and physics, as people in these fields have valuable expertise in digital design, machine learning techniques and the physical problems to be addressed. Also, as much as possible, work should be preserved in an open source manner, to be used cross-project and cross-experiment and further built upon in the future.

However, the needs of particle physics experiments are not always relevant to industrial partners, which implies that the retention of highly-skilled personnel is made even more important. The particle physics community has an interest in edge cases to typical uses in industry, such as electronics that perform well under constant bombardment from radiation or in cryogenic fluids. There is also a need for a high degree of reliability, as many devices are installed in detectors in areas that are inaccessible for replacement for decades at a time. It is important for the community to continue to follow development in industry and to build strong collaborative networks, but it is as important to develop resources to pursue R&D directions that are specific to use cases in the particle physics domain.

As we explore new TDAQ architectures and hardware with increasing complexity whose performance depends on interactions on a systems level, a dedicated facility that can support TDAQ design and development while also offering opportunities for integration testing across low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage should be established. While the necessary support hardware for the facility may be localized, the participating domain experts should encompass a distributed community. Given many of the common challenges across physics frontiers, such a Trigger and Data Acquisition Emulation and Integration Test Facility should cross experiment and project boundaries, offering support for emulation of detectors and TDAQ systems, and the development and maintenance of common hardware, firmware, and software, and to support TDAQ R&D for future detectors. This facility will develop and maintain an accessible knowledge-base by enabling and supporting connections and communication between engineers and scientists in many National Labs and university labs working within different subfields that encounter similar problems.

Finally, we note that the success of a detector upgrade or new experiment ultimately depends not just on the delivery of the new components, but on the successful installation, commissioning, and integration of them into the experiment as well as their efficient operation. This applies to trigger-DAQ as much as any other instrumentation area. These tasks need to be well thought out (preferably as part of the initial proposal to evaluate the overall cost of a new system) and supported. Lack of attention in any of these areas can lead to substantial and costly delays as well as a failure to reach the design goals, which jeopardizes the physics output. Thus the installation, commissioning, and integration tasks as well as the long-term operations (until the end of the experiment) must be a priority.

7.5 Micro-Pattern Gaseous Detectors

Gaseous Detectors are the primary choice for cost effective instrumentation of large areas and for continuous tracking of charged particles with minimal detector material. Traditional gaseous detectors such as the wire chamber, Resistive Plate Chamber (RPC), and TPC with multiwire proportional chamber (MWPC) readout remain critically important for muon detection, track-finding, and triggering in ongoing and planned major particle physics experiment, including all major LHC experiments (ALICE, ATLAS, CMS, LHCb) and DUNE.

Micro Pattern Gaseous Detectors (MPGDs) are gas avalanche devices with order $\mathcal{O}(100\ \mu m)$ feature size, enabled by the advent of modern photolithographic techniques. Current MPGD technologies include the Gas Electron Multiplier (GEM), the Micro-Mesh Gaseous Structure (MicroMegas), Thick GEMs (THGEMs), also referred to as Large Electron Multipliers (LEMs), the Resistive Plate WELL (RPWELL), the GEM-derived architecture (μRWELL), the Micro-Pixel Gas Chamber (μ-PIC), and the integrated pixel readout (InGrid).

MPGDs have already significantly improved the segmentation and rate capability of gaseous detectors, extending stable operation to significantly harsher radiation environments, improving spatial and timing performance, and even enabling entirely new detector configurations and use cases.

In recent years, there has therefore been a surge in the use of MPGDs in nuclear and particle physics. MPGDs are already in use for upgrades of the LHC experiments and are in development for future facilities, such as the Electron Ion Collider (EIC), the International Linear Collider (ILC), FCC, and the Facility for Antiproton and Ion Research (FAIR). More generally, MPGDs are exceptionally broadly applicable in particle physics, hadron physics, heavy-ion physics and nuclear physics, charged particle tracking, photon detectors and calorimetry, neutron detection and beam diagnostics, neutrino physics, and dark matter detection, including operation at cryogenic temperatures. Beyond fundamental research, MPGDs are in use and considered for scientific, social, and industrial purposes; this includes the fields of material sciences, medical imaging, hadron therapy systems, and homeland security.

Five commissioned white papers on MPGDs were developed during the 2021 Snowmass decadal survey. These summarize ongoing R&D on MPGDs [30], the future needs for MPGDs in nuclear physics [31], and future needs for MPGDs in three broad areas of particle physics: low-energy recoil imaging [32], TPC readout for tracking at lepton colliders [33], and tracking and muon detection at hadron colliders [34]. A white paper with further details on a proposed TPC tracker for Belle-II was also submitted [35]. These whitepapers are summarized in our Snowmass Topical Group report on MPGDs [36]. An abbreviated version of this summary follows below.

IF05-1 MGPDs constitute an enabling technology that is key for large segments of the future US Nuclear Physics (NP) and HEP programs, and which also benefits other communities. MPGDs provide a flexible go-to solution whenever particle detection with large area coverage, fine segmentation, and good timing is required.

IF05-2 The technology is relatively young and should be advanced to performance limits to enable future HEP experiments. Support of generic and blue-sky R&D is required to achieve this.

IF05-3 The global HEP community would benefit from US strategy coordination with the ECFA detector R&D implementation process in Europe.

IF05-4 In order to maintain and expand US expertise on MPGDs, The US NP and HEP communities would benefit strongly from a joint MPGD development and prototyping facility in the US.

7.5.1 Recent Advances, Current R&D, and Future Needs

Recent developments in the field of MPGDs, and the role of the RD51 collaboration, a CERN research collaboration for the development of MPGD detectors, are summarized in Ref. [30]. MPGDs were developed to cost-effectively cover large areas while offering excellent position and timing resolution, and the ability to operate at high incident particle rates. Significant development time was invested in optimizing manufacturing techniques for MPGDs, in understanding their operation, and in mitigating undesirable effects such as discharges and ion backflow. The early MPGD developments culminated in the formation of the RD51 collaboration hosted by CERN, which has become the critical organization for promotion of MPGDs and which coordinates all aspects of their production, characterization, simulation and use in an expanding array of experimental configurations. The CERN MPGD Workshop is a source of essential expertise in production methods, mitigation and correction of manufacturing issues, and the development of MPGDs for specific experimental environments.

An impressive array of MPGDs has been developed, from the initial GEM and MicroMegas, now used in a wide variety of applications and configurations, through the more recent THGEMs, and μRWELLs with resistive layers to mitigate discharge effects. MPGDs are now also used jointly with other detector elements, for example with optical readout and in LAr detectors. In parallel with MPGD detector development, there has been an important creation of a standardized, general electronics system, the Scalable Readout System (SRS). This system has seen widespread use and is of great utility in allowing integration of a variety of frontend (FE) electronics into one data acquisition system. For Snowmass 2021, a number of Letters of Interest were received that illustrate ongoing developments and expansion of use of MPGDs. Submissions on high-precision timing, high-rate applications, expansion of the SRS readout system triggering capabilities, and reduction of ion backflow are summarized in Ref. [30]. Many other improvements of MPGDs are being actively pursued. Several of these efforts are commented on below. A detailed, comprehensive summary of expected MPGD needs of planned HEP experiments versus time can be found in the 2021 ECFA detector research and development roadmap [37], specifically in Fig. 1.1.

7.5.2 MPGDs for NP Experiments

Many current and future NP experiments in the US have or are implementing MPGDs for tracking and particle identification (PID) purposes. We have summarized the role that MPGDs play in NP experiments, and the R&D needed to meet the requirements of future NP experiments in Ref. [31]. Examples include advanced MPGDs for Tracking at the EIC, to be built at Brookhaven National Laboratory (BNL), which requires its tracking system to have low mass ($X/X_0 \leq 1\%$), large area $\mathcal{O}(1\ m^2)$, and excellent spatial resolution $\mathcal{O}(100\ \mu m)$. MPGDs such as the GEM, MicroMegas, and μRWELL can meet these requirements. The Facility for Rare Isotope Beams (FRIB) at Michigan State University will become the world's most advanced facility for the production of rare isotope beams (RIBs). MPGD technologies play an essential role in the science program's success at FRIB. Applications of MPGD technologies include low-pressure tracking and PID at the focal planes of magnetic spectrometers, Active-Target TPCs, and TPCs for the detection of exotic decay modes with stopped RIBs. Future spectrometers for NP experiments at the Thomas Jefferson National Accelerator Facility (JLab) require large area $\mathcal{O}(m^2)$, low mass ($X/X_0 \leq 1\%$), excellent spatial resolution $\mathcal{O}(100\,\mu m)$, excellent timing $\mathcal{O}(10\ ns)$, high rate $\mathcal{O}(1\ MHz/cm^2)$ tracking detectors for operation in high background rate and high radiation environment. Only MPGD technologies such as GEMs, MicroMegas, or μRWELL detectors can satisfy the challenges of high performances for large acceptance at reasonably low cost.

Dedicated MPGD Development Facility Currently, the majority of MPGD developers and users in the US rely on production facilities and expertise, diagnostic facilities, and standardized readout electronics associated with the RD51 collaboration and CERN. This significantly slows down the R&D cycle and limits the speed of innovation in the US. It also means all production for US-led experiments has to be outsourced. A US-based MPGD Center of Excellence is needed and would address this issue. We envision a facility similar in nature to the Gaseous Detector Development (GDD) lab at CERN or the Silicon Detector facility at the Fermi National Accelerator Laboratory (FNAL). Such a facility would benefit both the nuclear physics and particle physics communities in the US. There are also ample opportunities for commercialization and collaboration with industry. We envision such a facility hosted by one of the Department of Energy's (DOE) National Labs, such as JLab or BNL.

7.5.3 MPGDs for Recoil Imaging in Directional Dark Matter and Neutrino Experiments

MPGDs can be used to read out the ionization in low-density gas TPCs with exquisite sensitivity and spatial resolution. In the most advanced MPGD TPCs, even individual primary electrons – corresponding to an energy deposit on the order of ∼30 eV – can be detected with negligible background from noise hits, and 3D-ionization density can be imaged with $\sim(100\ \mu\text{m})^3$ voxel size. This new experimental technique, enabled by MPGDs, has a large number of interesting applications in fundamental and applied physics.

One of the most intriguing applications is to scale up TPCs with MPGD readout to construct a competitive, low-background, high-definition ionization imaging experiment, CYGNUS, which would be directionally sensitive to both dark matter and neutrinos. There is an opportunity here for the US to take the lead and initiate a novel experimental program focused on recoil imaging, with broad scientific scope, one that we have only just started to map out. Because large areas, $\mathcal{O}(1000\ \text{m}^2)$, of MPGDs are required, there are clear synergies with this proposal and the needs in nuclear physics, where MPGDs will be used broadly, and where R&D, production, and test facilities in the US are also desirable. Other notable applications of recoil imaging include the International Axion Observatory (IAXO), directional neutron detection, the measurement of the Migdal effect, X-ray polarimetry, the detection of rare nuclear decays. Several groups are also exploring TPC designs to use high density gases such as SeF_6 or argon and can provide the sub-mm to 10 micron resolution, for example via 'dual readout' TPCs which can detect both the positive ions as well as the electrons generated by a recoil event. TPCs using gaseous argon could be of interest for studies of the neutrino sector, for example τ-tracking for the study of $\nu_\tau\tau$ charged current interactions. Further detail on the emerging field of recoil imaging can be found in [32].

7.5.4 MPGDs at Future HEP Colliders

Advances in our knowledge of the structure of matter during the past century were enabled by the successive generations of high energy particle accelerators, as well as by continued improvement in detector technologies. In this context, MPGDs have become a preferred solution for enabling both continuous, low-mass charge-particle tracking in TPCs and large-area muon detection systems. Two of the most prominent MPGD technologies, the GEM and MicroMegas, have been successfully operated in many different experiments, such as Compass, LHCb, and TOTEM. In addition, the low material budget and the flexibility of the base material makes MPGDs suitable for the development of very light, full cylindrical fine tracking inner trackers

at lepton colliders such as KLOE-2 at the Double Annular Φ Factory for Nice Experiments (DAFNE) and BESIII at the Beijing Electron–Positron Collider II (BEPCII).

The TPC concept is viewed in particle physics as the ultimate drift chamber since it provides 3D-precision tracking with low material budget and enables particle identification through dE/dx measurements with cluster counting techniques. At ILC and the Chinese Electron Positron Collider (CepC), as well as for Belle-II upgrades, TPCs with MPGD readout are key to proposed detector designs [33–35].

Gaseous detectors are also the primary choice for cost effective instrumentation of very large areas, with high detection efficiency in a high background and hostile radiation environment, needed for muon triggering and tracking at future facilities. They can provide a precise standalone momentum measurement or be combined with inner detector tracks resulting in even greater precision. Adding precise timing information, $\mathcal{O}$(ns), allows control of uncorrelated background, mitigates pile-up and allows detection of extremely long lived particles that behave like slow muons propagating through the detector volume over a time as long as a few bunch crossings. Scaling up of MPGDs to very large single unit detectors of $\mathcal{O}(\mathrm{m}^2)$, has facilitated their use in muon systems in the LHC upgrades. Major developments in the MPGD technology have been introduced for the ATLAS and CMS muon system upgrades, towards establishing technology goals, and addressing engineering and integration challenges. MicroMegas and GEM have been recently installed in the ATLAS New Small Wheel and the CMS GE1/1 station respectively, for operation from LHC Run 3 onward, as precise tracking systems. Those radiation-hard detectors, able to cope with the expected increased particle rates, exhibit good spatial resolution, $\mathcal{O}$(100 µm) and have a time resolution of 5–10 ns. In the CMS muon system additional stations, GE2/1 and ME0, based on GEMs with high granularity and spatial segmentation, will be installed to ensure efficient matching of muon stubs to offline pixel tracks at large pseudo-rapidities during HL-LHC operation. Several solutions (μRWELL, μ-PIC, and small-pad resistive MicroMegas were also considered for the very forward muon tagger in the ATLAS HL-LHC Upgrade Muon Technical Design Report (TDR). Here, the main challenges are discharge protection and miniaturization of readout elements, which can profit from the ongoing developments on Diamond-Like Carbon (DLC) technology. The μRWELL is the baseline option for the HL-LHC Upgrade of the innermost regions of the Muon System of the LHCb experiment (beyond LHC Long Shutdown 4).

Muon systems at future lepton colliders, such as ILC, the CERN Linear Collider (CLIC), CepC, FCC-ee, and the Super Charm Tau Factory (SCTF) or the Large Hadron Electron Collider (LHeC), do not pose significant challenges in terms of particle fluxes and the radiation environment. Therefore many existing MPGD technologies are suitable for building future large muon detection systems. On the other hand, the expected particle rates for the muon tracking and triggering at future hadron colliders, such as the FCC-hh, make the existing technologies adequate in most regions of the spectrometers, but require a major R&D for the very forward endcap region. In a multi-TeV muon collider, the effect of the background induced by the muon beam decays is extremely important. A new generation Fast Timing MPGD (FTM, Picosec) is considered to mitigate the beam induced background, by rejecting hits uncorrelated in time. **Required R&D** should focus on stable operation of large area coverage, including precision timing information to ensure the correct track-event association, and on the ability to cope with large particle fluxes, while guaranteeing detector longevity using environmentally friendly gas mixtures and optimized gas consumption (gas recirculating and recuperation system.

7.6 Calorimetry

The Snowmass IF06 Calorimetry Topical Group has considered major issues in present and future calorimetry. Input has been taken from a series of talks, group discussions, Letters of Intent (LOI), and White Papers. Here we report on two major approaches to calorimeter systems – Particle Flow (PF) and

Dual Readout (DR), the critical extra dimension of precision timing, and the development of new materials for calorimeters. What follows is a distillation of the full report of the Topical Group on Calorimetry [38], highlighting the key points and recommendations.

The primary purpose of EM and hadronic calorimetry is the measurement of the energy of charged and neutral particles and overall event energy. However, they are also important systems for overall event reconstruction, particle identification and triggering. The physics goals and the experimental conditions at future colliders require technical advances in calorimeter technology to fully exploit the physics potential of these facilities. For future e^+e^- colliders, so-called Higgs Factories, the overall precision of event reconstruction is the main focus, while future hadron colliders at energies and luminosities significantly beyond the HL-LHC impose new challenges in terms of the experimental environment.

The field of calorimeter research and development remains very active. The precision energy measurement requirements of future physics programs is stimulating innovation in the particle flow and dual readout systems. The increasing availability of precise timing is adding an important new dimension to system implementation, while the development of a range of fast, radiation-hard active materials is leading to increased flexibility and exciting possibilities for calorimeter system designs.

IF06-1 Future calorimetry at fixed target and colliding beam experiments should be **fundamentally multidimensional**, providing shower position, time, energy, and a detailed look at shower constituents through the exploitation of an application-specific **combination of PF techniques, materials with intrinsically good time or energy resolution, or DR techniques.** R&D support is needed to achieve these goals.

IF06-2 Sustained R&D is needed to move multidimensional calorimetry **from prototype to realistic detector.** Scaling to hundreds of thousands or tens of millions of channels while maintaining the required quality is a huge challenge.

IF06-3 Electronics must be developed to allow new features such as fast timing **without significantly adding to the power budget or cooling load.** It will be necessary to have **HEP personnel trained in the new technologies** and close tracking of new electronics options emerging in industry.

IF06-4 Effective partnerships with chemists, materials scientists, industries large and small, and radiation facilities must be continued and strengthened to **explore the landscape of materials** that enable precision calorimetry and to lower the cost.

7.6.1 Precision Timing

The potential for precision timing at the 10 ps level or better opens new possibilities for precise event reconstruction and the reduction of the negative effects of challenging experimental environments. Precise timing can directly benefit calorimetry in several ways ranging from detailed object reconstruction to the mitigation of confusion from pile-up. It can also lead to improved performance for both PF and DR-based calorimeters.

Given these possible performance enhancements, the focus is now on the study of timing implementation both at the device level and the calorimeter system level, together with detailed simulations. A range of possible implementations can be envisaged, addressing the needs of calorimetric measurements, confusion reduction, particle identification, and long-lived particle searches. The timing precision required varies

across these applications. R&D is needed to establish whether an average timing precision can satisfy all the requirements at some acceptable level, or, for instance, dedicated high precision timing components are needed in combination with a general systemwide implementation.

The actual implementation of timing in calorimeter systems can take a number of forms. Timing information can be collected by all active calorimeter cells which, when implemented in a highly granular calorimeter enables a full 5-dimensional reconstruction of shower activity in the detector, with corresponding benefits for pattern recognition, spatial shower reconstruction and separation and energy measurement. However, the very large number of cells might force a compromise with only a fraction of cells instrumented for timing. A less challenging and expensive solution could be the use of timing layers, for instance before and after the EM calorimeter, and at certain depths in the hadronic calorimeter.

Careful studies are needed to assess the cost-to-benefits of possible system designs. Adding timing functionality at both the cell and layer levels has implications for material profiles/sampling ratios, power consumption, system complexity and expanded data volume. Due to recent developments a number of possible timing technologies have potential applicability to calorimeter systems. However, significant R&D is needed to address the realities of these choices and this is seen as a major area of future calorimeter development. Successful implementation can lead to highly performant calorimeter systems well matched to the demands from both future physics studies and experimental environments.

7.6.2 Active Materials

The construction of future calorimeters matched to the demands of high radiation tolerance, the need for fast timing, and constrained cost puts strong requirements on the properties of active calorimeter materials. Suitable materials should therefore combine high density, fast decay time, and good radiation hardness with good optical quality and high light yield. To cope with unprecedented high event rate expected by future experiments, an ultra-fast total absorption calorimeter with sub-nanosecond decay time is preferred. A range of inorganic scintillators using rare-earth doping in crystals has been developed possessing many of these desired properties. However, use of these materials in future large-scale calorimeter systems demands attention to material costs to assure affordability and to radiation hardness for long attenuation length of scintillation light after high radiation dose. Scintillating glass is a new type of active material that is being engineered to have similar performance and radiation hardness to lead tungstate. Work continuing to scale up production to the sizes needed for large EM calorimeter in a cost-effective way is in progress.

Organic-based scintillator calorimeters, including plastics scintillator, liquid scintillator, and water-based liquid scintillator, have fast pulse response with comparable light-yield to inorganic crystals. The plastic scintillators, polyvinyltoluene or polystyrene base, have seen very wide use, having the advantages of ease of use and relatively low cost. A new thermoplastics acrylic scintillator aiming to load scintillator materials and high-Z elements directly into acrylic monomers is under development. The combination of plastic scintillators with SiPM readout has significantly expanded the flexibility of calorimeter design. An alternative method to fabricate plastic detectors with tight controls on shape and dimension using a computer-aided 3D-printing design is highly desired. Finally, liquid scintillators have very low unit cost with improved properties in terms of stability and material compatibility that have been largely advanced through neutrino and other rare-event physics over the past decade and been widely used where very large volumes (tens of kilotons) are required. An interesting development is the potential of metal doped (water-based) liquid scintillators for use as active materials in sampling calorimeters.

7.6.3 Particle Flow

PF calorimetry makes use of the associations of charged tracks and calorimeter energy deposits to achieve precise reconstruction of hadronic jets and measurement of their energy. Such associations can also be effectively used to reduce the effects of pileup. Implementation of a Particle Flow Algorithm-based (PFA) calorimeter requires a small cell size and high granularity leading to very high channel counts. Challenges remain in realizing calorimeter systems with up to 100 million cells. Developent is onging for such systems in the areas of power and heat management, integration of on-board ASICs, and components of signal extraction. A variety of approaches to PFA calorimeters are under developent ranging from scintillator-SiPM systems to a range of gas-based systems using GEMs, MicroMegas and RPCs. Also being explored are the potential benefits of precise timing (see above) and moving some elements of a PFA into the front-end electronics.

The HEP community has demonstrated its strong interest in pursuing this technology in multiple applications in various stages of development. These include the HL-LHC CMS High Granularity Calorimeter (HGCal), e^+e^- collider alternatives (SiD and ILD for the ILC, the CLIC detector concept, CLD for the FCC-ee, and the baseline CepC detector concept), FCC-hh, and a possible muon collider. Among these, the CMS HGCal upgrade for the HL-LHC is at the most advanced stage of development, with delivery of the production silicon sensors slated to begin in January 2023. Another example of high granularity is the development of MAPS electromagnetic calorimetry for the SiD detector. This technique has shown the potential for excellent photon reconstruction and separation, and excellent π_0 reconstruction while delivering very good electromagnetic energy resolution. The addition of timing layers would also be a natural extension of the MAPS approach.

PF calorimetry development has synergies with developments in other areas of HEP instrumentation. Silicon detectors, SiPMs, fast scintillators, and gas ionization detectors are all good candidate active media, depending on the use case. Smart, low-power, radiation-tolerant front end electronics are needed to realize compact designs. PF reconstruction provides a benchmark for optimizing novel computational methods, like the use of ML in triggering or particle reconstruction. The computational problem of PF reconstruction, in which charged and neutral hadrons, electrons, muons, hadronic tau decays, photons, and jets must be identified from associations between tracks and highly granular calorimeter deposits, may be particularly well suited to ML methods as opposed to a traditional deterministic algorithm. In turn, PF reconstruction requires performance advances that can speed up detector simulation or improve jet energy resolution. Breakthroughs in any of these related technologies can drive significant progress in PF calorimetry, be it cost reduction, simplification of engineering, increased radiation hardness, or improved physics performance.

To realize the full potential of PF calorimetry, and to ensure that it is "shovel-ready" when the next large experiment is approved, R&D is needed to solve outstanding problems. Extensive beam testing, especially of large-scale technological prototypes, is needed to study integration issues and how they affect EM and hadronic energy resolution. As stated above, more research is needed in FE design, especially for high-occupancy and high-radiation applications like a future hadron or muon collider. Finally, the challenge of rethinking traditional assembly and quality control procedures to find solutions that scale to tens to hundreds of millions of channels cannot be overlooked. There is a growing need to incorporate lessons from product and process engineering into instrumentation labs, either through personnel decisions or by adapting the training of traditional physics graduate students and postdocs. Similarly, academic-industrial partnerships need to be formed with this scale in mind.

7.6.4 Dual Readout

The DR approach to the precise measurement of jet energies makes use of the scintillation light and Cherenkov light from showers. The relative amounts of scintillation and Cherenkov light is used to correct the shower energy. The original approach to implementing DR calorimetry used a matrix of scintillating fibers and clear optical fibers (for the Cherenkov component) in a block of absorber material. However, with the reduced need for spatial associations (as in PF), DR can make beneficial use of an EM front section using homogeneous scintillating crystals which have excellent EM energy resolution. Development of DR systems has followed both of these approaches. In the second case, the separation of the scintillation and Cherenkov signals can be achieved by the use of optical filters and SiPM readout or exploitation of the different time structure of the two signals. Development and testing of large-scale systems is needed to demonstrate the feasibility of both the all-fiber and homogeneous EM section plus fibers approaches to DR.

Significant R&D is still needed to fully realize the potential of DR. Large-scale prototypes need to be constructed to understand which parts of the engineering are cost drivers, which need further R&D, and how a realistic system will perform. Such efforts have already begun in the context of e^+e^- circular collider studies. The Innovative Detector for an Electron-positron Accelerator (IDEA) fiber calorimeter considers a stacked capillary arrangement as well as a 3D-printed copper alveolar tower into which fibers are inserted. In the case of homogeneous scintillating crystals, a key open question is how to ensure that readout of the red end of the Cherenkov spectrum, far from the scintillation peak, will yield a large enough signal with which to perform the DR correction. Due to the large size of collider detectors, another important question is how to drive down the cost of high-performing crystal scintillators. In the long-term, research into new optical materials, such as photonic crystal fibers for increased Cherenkov light collection, quantum dot and semiconductor nanoparticle wavelength shifters, and fibers that maintain polarization information, can improve the performance or reduce the cost of DR fiber calorimeters.

The wide availability of high-performance SiPMs serves to simplify DR mechanical design and allows for channel granularity not initially envisioned. There is no reason that the advantages of PF and DR cannot be combined in certain applications to yield even more flexibility. Readout of each fiber by a SiPM opens the door to jet imaging and position reconstruction using algorithmic or deep learning techniques. This can enable gluon-jet discrimination, studies of jet substructure, or identification of tau leptons or boosted objects. Indeed, the extra FE information that DR relies on requires advances in electronics for efficient data processing and reduction. Areas of R&D in this direction include system-on-chip waveform digitizers with real-time analysis, FPGAs on the FE, and digital SiPMs. With flexibly designed readouts, it may also be possible to use the time structure of the Cherenkov and scintillation signals to estimate the shower's EM fraction online and improve triggering.

7.7 Readout Electronics and ASICs

In pursuit of its physics goals, the HEP community develops increasingly complex detectors, with each subsequent generation pushing to ever finer granularity. For example, the emergence and growing dominance of PF reconstruction methods has stressed the increasing importance of very fine detector granularity, not only for tracking detectors but also for calorimetry, and has also initiated the push to 4D-detectors that combine precision measurements of both spatial and time coordinates to their measurements of energy and momentum. While these developments have led to enormous growth in detector channel counts, the analog performance requirements for energy and momentum measurements, as well as spatial and timing precision, are being maintained or (more typically) even tightened.

These challenging detector requirements drive the corresponding development of readout electronics. A variety of factors, including the growing specialization of the functionality required, and the explosive growth in channel counts and typically modest (if any) increases in the material budget and the power and cooling budgets, lead to the increasing reliance on custom-developed ASICs. This trend is further exacerbated by challenges in the various experimental environments, including radiation hardness requirements, cryogenic and deep-cryogenic operations, and space-based detector systems. The development of custom ASICs in advanced technology nodes allows HEP detector subsystems to achieve higher channel density, enhanced performance, lower power consumption, lower mass, much greater radiation tolerance, and improved cryogenic temperature performance than is possible with commercial integrated circuits (ICs) or discrete components. The higher level of integration also leads to fewer components and fewer connections, leading to higher reliability, as required by experiments that can run for decades and that provide access to the on-detector electronics at most annually, and sometimes never.

This writeup summarizes the work of IF07, the Instrumentation Frontier's Topical Group for Readout Electronics and ASICs [39]. The community efforts as part of IF07 were organized across seven white papers submitted to the Snowmass process. The first [40] discusses issues related to the need to maintain the talented workforce required to successfully develop future HEP electronics systems, and to provide the appropriate training and recruitment. The remaining papers focused on electronics for particular detector subsystems or technologies, including calorimetry [41], detectors for fast timing [42], optical links [29], smart sensors using AI [43], and RF readout systems [44]. In the following section, a brief overview is provided of each of the white papers in turn. A white paper on silicon and photo-detectors was originally considered. This content is now captured by other frontiers with contributions from ASICs and readout electronics.

There are some overarching goals for advancing the field of readout and ASICs. Efforts with broad impact include:

IF07-1 : Provide baseline support and specialized **training opportunities** for the instrumentation work force to keep the US electronics instrumentation and ASIC workforce current.

IF07-2 : Improve mechanisms for **shared access to advanced technology** providing broader access by the community to foster real exchange of information and accelerate development.

IF07-3 : Continue to develop methodologies to **adapt the technology for operation in extreme environments**. Deep cryogenics, ultra-radiopure materials, radiation-harsh environments with limited power budget and long lifetime for all cases.

IF07-4 : Develop novel techniques to manage very high **data rates**. Data reduction and optimization needs to be as close as possible to the generation point with acceptable power consumption.

IF07-5 : Create framework and platform for **easy access to design tools**. Develop specialized online resources for the HEP community (e.g. system simulations and design repository). Provide the basis for true co-design R&D efforts: from simulation to verification and implementation.

A brief overview of each of the IF07 white papers is provided below. A more detailed discussion of each of the various topics can be found in the white papers themselves, and in the references therein.

7.7.1 Workforce and Training Needs

Two decades ago as we embarked on the design of the LHC detector systems, *on detector* readout was focused on the integration of custom sensors and multiple types of ASICs with communications rates at or

below 100 Mbps. Significant effort went into the design of printed circuits on boards or flexible substrates. A new generation of ASICs were coming into use that could survive radiation tolerance levels consistent with the needs of LHC provided specialized layout techniques were employed. Designers were faced with learning new tools and rules for commercial ASICs that were attainable in a few months and system interfaces were being designed that allowed multiple institutions to design parts of a readout system nearly independently. As LHC systems were being placed into service commercial ASICs and communications systems were leap frogging forward and significant change was moving the state of the art forward faster than our communities and budgets could maintain pace with. Today's HL-LHC designs have been able to take advantage of advances that are still several technology generations behind the commercial state of the art to move what previously was multi-chip functionality onto a single silicon substrate to make systems on a chip that operate at much higher clock rates and can hold and selectively read out more data and contain most or all of the readout blocks for modules of thousands of small size sensors. The price for successful submission of these far more complex, low power integrated circuits has been the requirement for a workforce with knowledge of a broad set of new tools for design and verification as well as formalized design management and integration tools that do not allow new versions or blocks to compromise the overall performance or design progress of these now highly complex systems on a chip. This IC revolution has also resulted in complex new capabilities built into today's FPGAs that comprise a large part of the *off-detector* DAQ systems designed over the past decade. Here too the required knowledge base has expanded sufficiently far so that coding is no longer an easy skill to learn for this or next generation designers. We foresee the need for continuing workforce training past the qualifying academic degrees to update commercial design skills. Many designs require HEP specialized knowledge to enable successful first time designs for extreme temperature, radiation and high-radiopurity environments. Our community needs to exploit the internet to provide an archive with searchable access to design examples from previous generations of detectors to replace the institutional knowledge passed down from previous teams. This is especially important given that the time between large detector system developments may exceed career lifetimes. In these extended interim periods it is recognized that core HEP instrumentation specialists need to update their skills with practical projects to ensure their familiarity with the evolving state of the art in ASIC designs. This can be encouraged by DOE-provided annual FOAs to support the design of service blocks that will be necessary in yet to be defined FE ASICs for next generation sensor arrays: High-speed communication links, data storage blocks, Phase Lock Loops (PLL), power converters and regulators etc. Silicon tested designs for next generation ASICs will both speed up design cycles and help maintain workforce skill levels consistent with current (at the time of need) ASIC design tool familiarity to minimize the number of design submissions required to assure reliable ASIC performance. We encourage the HEP academic community to provide instrumentation-based PhD degrees to formally make available expertise in the experimental HEP community. In addition it will be beneficial to have instrumentation conferences with training available to introduce new design approaches or technologies. This training should include continuing education certification to help qualify candidates for positions in experimental HEP. We see the recent support from DOE for instrumentation-based traineeship to be an important step towards having a better trained, better informed workforce not only for designing systems but also for the benefit of future peer-reviewed systems.

7.7.2 Calorimeter Readout Electronics

Calorimeters will continue to serve key roles at future colliders, as well as in many other applications. The traditional challenges of calorimeter readout systems, including providing high precision energy measurements over a very wide dynamic range, are increasingly compounded by the demands of much finer granularity and correspondingly higher readout rates, as well as the demand of providing precision time measurements in the move toward 5D-calorimetry. The on-detector location of the FE electronics,

necessitated by signal-to-noise and other requirements, imposes additional challenges, including tolerance to radiation or magnetic fields, reliability over long periods without maintenance, and power and cooling budgets.

Key innovations that are driving ongoing and future readout developments include PF algorithms, in which calorimeter measurements of energies are combined with the momentum measurements from tracking detectors, and DR detectors, which provide a more flexible combination of the EM and hadronic components of a shower. Both of these methods aim to significantly improve the energy resolution, and both can be implemented either with or without timing information as an added component.

PFA are pushing calorimeter designs to ever finer granularities, and therefore greatly increasing channel counts. As an example, the HGCal being developed currently for the CMS HL-LHC upgrade includes over six million readout channels, a dramatic increase over the $\approx 200k$ channels of the ATLAS LAr calorimeters that set the scale for "finely segmented" among the original LHC detectors.

Meeting the challenges for FE calorimeter readouts has relied on custom ASICs for over 30 years, and ASICs will only become increasingly important. Fortunately, the higher level of integration available today has permitted some consolidation; for example, while the current ATLAS LAr FE required development of 11 different custom ASICs, spread over a variety of technologies, the HL-LHC developments underway requires only three. The higher level of integration is most clearly seen in the digital realm, where for example CERN's lpGBT chip in 65 nm CMOS fulfills a number of functions, including clock and control distribution, slow control monitoring, and data serialization and formatting, that were previously spread over a number of different ASICs. However, even in the analog realm some consolidation has been achieved, such as the 130 nm ASIC developed for LAr that combines the functions of both preamplifier and shaper.

Preserving the ability to develop ASICs to meet the challenges of future calorimeters relies on maintaining affordable access to the specialized ASIC processes in industry, and to qualify these processes concerning radiation tolerance and, in some applications, also their performance in cryogenic environments. A fortunate development has been the typically increasing radiation tolerance of new ASIC processes with smaller feature sizes; while the original LHC FE ASICs exploited a number of specialized processes, or used standard cells and design rules that had to be explicitly developed to improve the radiation tolerance, the HL-LHC developments can focus on commercial 130 nm and 65 nm CMOS processes and use commercial standard cell libraries. The move to ever smaller feature-size ASIC processes also greatly helps reduce the power consumption. However, the corresponding evolution to lower power rails presents a significant challenge for the very FE analog circuits that must handle input signals over a very wide, often around 16-bit, dynamic range.

Other challenges for future calorimeter readouts include the powering systems, ranging from power supplies, to digital-current-to-digital-current (DC-DC) converters and low dropout regulators (LDO) or on-chip regulation, that can provide the needed power in a practical and radiation-tolerant manner. Powering has long proved a difficult issue at the LHC, and carefully evaluating over many years the radiation tolerance of commercial devices has clearly demonstrated that the great majority would not survive the LHC conditions. As a result, industrial partnerships were launched for both the original LHC and for the HL-LHC to develop radiation-tolerant LDOs.

7.7.3 Electronics for Fast Timing

Picosecond-level timing will be an important component of the next generation of detectors. The ability to add an additional dimension to our measurements will help address the increasing complexity of events

at hadron colliders and provide new tools for precise tracking and calorimetry for all experiments. Timing is crucial for background rejection in DM searches and neutrino detectors. As resolution continues to improve, time will likely become an equal partner to position measurement in tracking and PFA. All this has been enabled both by the rapid and continuous advance of fast electronics and the ability to generate fast signals with good signal-to-noise. Fast silicon sensors with gain, (e.g. LGAD) and sensors without gain (e.g. 3D-sensors), MPGD, Cherenkov light and fast scintillators such as Lutetium-yttrium oxyorthosilicate (LYSO) crystals, microchannel plate (e.g. LAPPD), semiconductor-based photodetectors such as SPADs and SiPMs, and other sensors all provide very fast signals. There are several R&D efforts aimed at the development of fast ASIC electronics for future HEP applications with focus on using specific and advanced technology (e.g. silicon-germanium (SiGe), 28 and 22 nm CMOS) and implementing suitable concepts for the needed time resolution (e.g. full waveform digitization, TDC, monolithic solutions).

The design and optimization of the FE amplifier is particularly important for fast electronics. Distribution and maintenance of reference clocks will be a challenge for large systems. Timing must be monitored to compensate temperature and aging effects. Complex calibration techniques are being developed to provide 1 ps phase resolution.

Using a combination of instrumentation techniques and developments, including Constant Fraction Discrimination (CFD), waveform sampling combined with precise clock distribution and newly developed sensors we expect that it will be reasonable for future fast timing detector sub-systems to set a 10 ps timing resolution goal that will allow for unprecedented accuracy and significantly improve the physics reach of next generation high rate, collider detectors.

7.7.4 Optical Links

The dramatic increase in channel count due to new fine-grained detectors relies on optical links to transmit data from the on-detector FE electronics to the TDAQ systems off detector. Today's high-radiation detector environments require custom ASICs and materials for these links.

To date, these radiation requirements and reliance on custom solutions have resulted in link speeds per fiber that are significantly lower than used in commercial systems. Custom links developed for LHC were limited to less than 2 Gbps per fiber. Recently completed HL-LHC upgrades have pushed this to 10 Gbps. This substantial increase in per-fiber bandwidth has, however, not kept pace with the growth in data volume. The original ATLAS LAr readout used a single 1.6 Gbps link per 128 channels, while the corresponding HL-LHC readout will need 22 fibers at 10 Gbps each for 128 channels. These faster links are still well behind current technology that is pushing 56 Gbps. The 10 Gbps lpGBT development led by CERN in 65 nm CMOS will be used in most HL-LHC on-detector electronic readout applications and R&D is currently underway that aims to increase the bandwidth by a factor of two in the short term, perhaps in time for some HL-LHC sub-systems still within 65 nm CMOS. Studies are underway to push to 56 Gbps utilizing a 28 nm CMOS process. Realization of a functional optical link requires several building blocks, including a data fan-in and serializer, combined with a electrical-to-optical conversion coupled to an optical module that couples to the fibers. Apart from the ASICs, the critical components for the optical modules themselves have been mostly satisfied by commercially available VCSELs and pin diodes, which must be painstakingly selected for radiation tolerant materials. However, custom optical module designs that integrate these functions plus the optical connections are still required. These must satisfy tight spatial and mechanical constraints within location sensitive material budgets imposed, in particular, by the inner detectors at future high rate hadron colliders or at HL-LHC future upgrades.

Meeting future needs will require ongoing R&D, to facilitate the continued evolution to higher bandwidths, and in particular per-fiber bandwidths.

7.7.5 Smart Sensors Using AI

Modern particle physics experiments and accelerators create massive amounts of data which require real-time data reduction as close to the data source and sensors as possible.

Data transmission is commonly much less efficient than data processing. Therefore, placing data compression, extracting waveform features and processing as close as possible to data creation while maintaining physics performance is a crucial task in modern physics experiments. The implementation of AI and ML in near-detector electronics is a natural path to add capability for detector readout. While the application of AI/ML is growing rapidly in science and industry, the needs of particle physics for speed, throughput, fidelity, interpretability, and reliability in extreme environments require advancing state-of-the-art technology in use-cases that go far beyond industrial and commercial applications.

Progress has been made towards generic real-time processing through inference including boosted decision trees and neural networks (NNs) using FPGAs in off-detector electronics, however ML methods are not commonly used to address the significant bottleneck in the transport of data from FE ASICs to back-end FPGAs. Embedding ML as close as possible to the data source has a number of potential benefits:

1) ML algorithms can enable powerful and efficient non-linear data reduction or feature extraction techniques, beyond simple summing and thresholding; 2) This could in turn reduce the complexity of down stream processing systems which would then have to aggregate less overall information all the way to offline computing; 3) This enables real-time data filtering and triggering like at the LHC and the EIC otherwise not be possible or be much less efficient; or in the case of cryogenic systems, reduce the system complexity; 4) Furthermore, intelligent processing as close as possible to the source will enable faster feedback loops.

Most of the efforts are focused on digital CMOS technology, such as implementations based on general-purpose Tensor Processing Units (TPU) or GPUs, FPGAs, and more specialized ML hardware accelerators. The steady improvements in such hardware platforms' performance and energy efficiency over the past decade are attributed to the use of very advanced, sub-10-nm CMOS processes and holistic optimization of circuits, architectures, and algorithms. The opportunities for building more efficient hardware may come from biological NN. Indeed, it is believed that the human brain, with its $>1000\times$ more synapses than the weights in the largest transformer network, is extremely energy efficient, which serves as a general motivation for developing neuromorphic hardware. There is a long history of CMOS neuromorphic circuits. However, unleashing the full potential of neuromorphic computing might require novel, **beyond-CMOS** device and circuit technologies that allow for more efficient implementations of various functionalities of biological neural systems.

Many emerging devices and circuit technologies are currently being explored for neuromorphic hardware implementations. Neuromorphic inference accelerators utilizing analog in-memory computing based on floating gate memories are perhaps the closest to widespread adoption, given the maturity of such technology, the practicality of its applications, and competitive performance with almost 1000x improvement in power as compared to conventional (digital CMOS) circuit implementations. The radiation hardness of these techniques and their applicability for robust performance in extreme environments is yet to be evaluated.

There are several ongoing R&D efforts focused on on-detector AI/ML and the key elements of both the design and implementation, and the design tools themselves. Though early in this exploration, the existing

work highlights the needs for configurable and adaptable designs and open-source and accessible design tools to implement efficient hardware AI. Different classes of future applications require dedicated investments to advance our capabilities in this field.

7.7.6 Cryogenic Readout

Many applications, including direct DM detection, CMB and line-intensity mapping as well as neutrino experiments, require electronics designed to perform within cryogenic environments.

Some operate at deep cryogenic levels going from liquid helium (LHe) temperatures at a few Kelvin down to milli-Kelvin. TPCs used in neutrino detection and DM searches use noble liquids as a target material. Most current generation TPCs keep the active electronics in the warm, outside the cryostat. The sheer scale of the DUNE LAr TPCs being designed today makes it impractical to bring all the raw analog detector signals into the warm, and instead embeds the active FE electronics in the cold. For the DUNE wire-based LAr TPC readout, the required cold functionality is achieved by a set of three custom ASICs, one that amplifies and provides analog filtering, one that digitizes at 2 MSamples/s, and one that collects and serializes the data for transmission over copper cables to the warm electronics outside the cryostat.

The DUNE near detector will use a low-power pixel readout utilizing the self-triggering LarPix 64-channel pixel ASIC submerged in LAr. Four programmable readout paths on the chip allow a board-level fault tolerant readout path. Track reconstruction results from prototype boards populated with 100 ASICs each have shown very promising physics results.

A second, very low-power readout is being investigated by the Qpix Collaboration that utilizes a novel approach to record the times of arrival of a fixed unit of charge, enabling offline reconstruction of the ionization current sensed at the pixel with a sub-femto Coulomb unit charge sensitivity.

Deep-cryogenic CMOS circuits and systems have seen rapid development in recent years, with quantum computing being the primary technological and economic driver. Early work focused on studying and modeling the properties of devices, including Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET), resistors, and capacitors, in various CMOS technologies at cryogenic temperatures. The results suggested that devices in modern nm-scale fabrication technologies (including bulk CMOS, SOI, and fin-shaped field-effect transistor (FinFET)) function successfully at temperatures as low as 50 mK. The main deleterious effects of cryogenic operation on nanoscale MOSFETs include a moderate increase in threshold voltage and degradation in 1/f noise and matching properties, both of which can be overcome using well-known precision circuit design techniques. A potentially more serious problem is the self-heating of such devices due to internal power dissipation. For example, a recent study shows that the channel temperature of 40 nm bulk CMOS transistors can increase by over 40 K compared to a LHe ambient of 4.2 K when dissipating only 2 mW. Thus, integrated electrothermal modeling is an important requirement for successfully designing deep-cryogenic CMOS systems. Given the availability of reliable cryogenic CMOS device models, research has focused on using these models to develop and test functional blocks necessary for qubit control and readout, including cryogenic frequency synthesizers, low-noise amplifiers, and circulators. Cryogenic operation of embedded memory, including standard static random access memory (SRAM) cells, has also been demonstrated. The availability of these building blocks has motivated the recent development of complete cryogenic CMOS qubit control and readout interface and monolithic quantum processors that integrate on-chip silicon charge qubits with CMOS readout electronics. Precision sensing is another major driver for cryogenic CMOS circuits and systems where ultra-low-noise analog FE is a major application area.

7.7.7 RF Electronics

RF electronics utilizes the RF domain to sense or control EM radiation well below ionization energies to make highly sensitive measurements of natural phenomena. The sophistication and sensitivity of RF-related detection systems has improved dramatically with advances in wireless communications. HEP now has the opportunity to probe EM field signals, measuring amplitude, phase, frequency, and polarization with unprecedented signal-to-noise and orders-of-magnitude improvement in signal processing per unit of power consumption. Combining RF analog-digital and digital-analog high-precision and bandwidth performance and high-speed FPGAs to read out arrayed superconducting sensors such as: TES, Kinetic Induction Detectors (KID) and superconducting bolometer systems will give us a better view of the universe.

Measurements of the extreme red-shifted 21 cm (1420 MHz) hyperfine transition of neutral atomic hydrogen are helping explore the early Universe in the red-shifted range of 10-500 MHz, inferring times before the creation of stars where a homogeneous mix of materials allow robust theoretical predictions to be tested. Sophisticated very low-noise techniques are required to achieve the necessary electronics noise levels. To achieve reasonable levels of detection, undistorted signal backgrounds can only be found locally on the far side of the moon. Multiple proposals are being developed with the objective of installing sensitive antennae and electronics there with lunar orbiting satellite relay stations. The results of these explorations will benefit the ongoing development of cosmological models and may be an indicator of new physics.

7.8 Noble Elements

Particle detectors making use of noble elements in gaseous, liquid, or solid phases are prevalent in neutrino and DM experiments and are also used to a lesser extent in collider-based particle physics experiments. These experiments take advantage of both the very large, ultra-pure target volumes achievable and the multiple observable signal pathways possible in noble-element based particle detectors. As these experiments seek to increase their sensitivity, novel and improved technologies will be needed to enhance the precision of their measurements and to broaden the reach of their physics programs. The Priority Research Directions (PRDs) and thrusts identified in the BRN report [1] are still relevant in the context of this Snowmass 2021 Topical Group. The areas of R&D in noble element instrumentation that have been identified by the HEP community in the Snowmass white papers and Community Summer Study align well with the BRN report PRDs, and are highlighted by five key messages (with IF-wide themes in bold):

IF08-1 Enhance and combine existing modalities (light and charge) to **increase signal-to-noise and reconstruction fidelity**.

IF08-2 Develop new modalities for signal detection in noble elements, including methods based on ion drift, metastable fluids, solid-phase detectors and dissolved targets. Collaborative and blue-sky R&D should also be supported to enable advances in this area.

IF08-3 Improve the understanding of **detector microphysics** and calibrate **detector response in new signal regimes** [45].

IF08-4 Address challenges in scaling technologies, including material purification, background mitigation, large-area readout, and magnetization.

IF08-5 Train the next generation of researchers, using fast-turnaround instrumentation projects to provide the design-through-result training no longer possible in very-large-scale experiments.

The IF08 Topical Group report [46] identifies and documents recent developments and future needs for noble element detector technologies. In addition, we highlight the opportunities that this area of research provides for continued training of the next generation of scientists. The following subsections summarize the objectives and opportunities associated with each of the above messages, described in detail in the Topical Group report.

7.8.1 Enhancing Existing Modalities

Noble element detectors developed for neutrino physics and DM searches record mainly the charge from the ionization electrons and the light from the scintillation produced by the passage of charged particles through the medium. The technologies to read out the charge in neutrino experiments have mostly been based on wire readouts, while charge measurements in DM searches rely on gain mechanisms such as gas electroluminescence and proportional gain. To read out scintillation light, both neutrino and DM experiments have focused on the use of Photo Multiplier Tubes (PMT) and SiPMs with coverage ranging from sub-percent to up to 50% levels.

It is clear that for the future, advances in charge and light detection capabilities are highly desirable, and to this end a range of new approaches have been proposed.

7.8.1.1 Pixels

Although the concept of wire-based readout has been proven and has had wide usage in neutrino detectors, it has an intrinsic limitation in resolving ambiguities, resulting in potential failures of event reconstruction. In addition, the construction and mounting of massive anode plane assemblies to host thousands of finely spaced wires poses significant and costly engineering challenges. For these reasons, a non-projective readout presents many advantages, but the large number of readout channels and the low-power consumption requirements have posed considerable challenges for applicability in liquid noble TPCs. The endeavour to build a low-power pixel-based charge readout for use in LArTPCs has independently inspired multiple consortia to pursue complimentary approaches to solving this problem.

7.8.1.2 Light Collection

The information carried by photons is critical for a wide range of physics measurements in noble element detectors, providing a crucial means by which to perform detector triggering as well as position and energy reconstruction and identifying interactions of interest. It is essential to fully leverage this information in next-generation measurements, including neutrino interactions from low-energy CEvNS up to the GeV energy scale, neutrino astrophysics, and Beyond the SM physics searches such as for low-mass DM and neutrinoless double beta decay. These efforts will require substantial (even as high as 100-fold) increases in light collection, to enable percent or sub-percent level energy resolution, mm-scale position resolution, low-energy detector readout triggering, or highly efficient PID, including for events around $\mathcal{O}(\leq 1)$ MeV (keV) energies in detectors at the 10 kton (100 ton) scale. In the context of the broader program of noble element detectors, enhancements in photon collection will lead to dramatic improvements in event reconstruction precision and PID, in a broader range of physics signatures afforded by lower trigger thresholds, and in precision timing to unlock new handles for beam-related events.

Measurement of the light signals, however, presents a major challenge with currently available technologies. For example, in large-scale liquid argon neutrino detectors, it is typical to collect <1% of the produced photons. This limitation is driven in large detectors by geometric considerations and other active components, total heat load, data volume, and the cost of instrumented surface area. Several promising approaches to improving light collection can address one or more of the limitations noted above, and taken together, provide a set of complementary tools for next-generation experiments: photon collection efficiency may be improved by imaging a large volume on a small active detector surface using novel lensing technologies, deployment of reflective and wavelength-shifting passive surfaces, bulk wavelength-shifting through dissolved dopants, improvement of photon detectors and photon transport efficiency, or the conversion of photons into ionization charge for readout using a TPC.

7.8.1.3 Extreme Low Thresholds and Electron Counting

The lowest energy phenomena that can be studied with existing noble-element modalities, including low-mass DM, reactor neutrinos, and natural (e.g. solar) neutrinos, require detectors that are sensitive to single ionization electrons. Such detectors are sensitive to $\mathcal{O}(10$ eV) electronic recoils and $\mathcal{O}(100$ eV) nuclear recoils, but lack the scintillation-dependent nuclear and electronic recoil discrimination present at higher energies. Without nuclear and electronic recoil discrimination, systematic backgrounds and radioactivity obscure typically background-free nuclear recoil event searches, and the radiopurity of detector materials becomes critical. Beyond background particle interactions, high rates of single- and few-electron signals are observed. Such spurious electrons have defied clear explanation and appear related to charge build-up on surfaces or in unknown chemical interactions, among other potential effects. Dedicated R&D is needed to better understand the sources of these backgrounds and to develop mitigation techniques.

7.8.1.4 Charge Gain

Lower detection thresholds in track-reconstructing detectors (where the electroluminescence techniques of the previous section are less useful) may be achievable through amplification of the ionization signal in the form of charge gain, typically achieved in the gaseous phase of argon and xenon detectors. Multiple innovative methods are being developed to either enhance the capabilities of charge amplification in gaseous detectors (e.g. to achieve stable charge gain while retaining the primary scintillation channel) or to enable amplification directly in the liquid phase.

7.8.2 New Modalities

As a detection medium, noble elements present unique opportunities beyond the collection of scintillation photons and ionized electrons. The modalities described in this section find new ways to utilize the monolithic, ultra-pure elemental detection medium provided by noble elements, extending the reach of noble-element-based detectors to new signal regimes and enabling new methods of background discrimination in rare event searches.

7.8.2.1 Ion Detection and Micron-scale Track Reconstruction

The ability to reconstruct ionization tracks at micron- and sub-micron spatial resolution is the key to many currently unsolved detector challenges, including directional DM detection ($\mathcal{O}(10^{-6}\text{g/cm}^2)$ spatial resolution required), discrimination of single-electron backgrounds in $0\nu\beta\beta$ searches ($\mathcal{O}(10^{-1}\text{g/cm}^2)$ spatial resolution required), and potentially for detection of supernova and solar neutrino events in very large-scale neutrino detectors ($\mathcal{O}$(sub-mm) spatial resolution required). Attempts at direct (TPC-style) high-resolution reconstruction universally rely on ion drift rather than electron drift to escape the resolution-limiting effects of electron diffusion over large drift distance.

7.8.2.2 Metastable Fluids

Metastable fluid detectors amplify the energy deposited in particle interactions with the stored free energy in a superheated or supercooled liquid target. That amplification can be made selective by matching the different energy-loss mechanisms and length scales for signal and background interactions with the relevant phase-change thermodynamics, for example allowing bubble chambers to detect $\mathcal{O}$(1 keV) nuclear recoils (e.g. from DM or coherent neutrino scattering) while being completely blind to electron recoil backgrounds. Instrumentation efforts in this area typically focus on (i) extending phase-change based discrimination to new signal regimes, and (ii) improving control of spurious phase-change nucleation to enable larger quasi-background-free exposures.

7.8.2.3 New Modalities in Existing Noble Element Detectors

It is highly desirable to find novel ways to take advantage of both the field-wide expertise that has developed around noble-element-based detectors and the world-class infrastructure surrounding existing and near-future searches for new physics. In general, after an experiment has achieved its scientific goals, the experimental community can continue to leverage the infrastructure for future experiments. There are many liquid noble installations around the world that can lend themselves to this sort of upgrade. Specific past examples and future opportunities appear in [46], including the use of dissolved targets in existing detectors and the development of a solid-phase TPC.

7.8.3 Challenges in Scaling Technologies

Next-generation large-scale detectors are planned to search for DM and $0\nu\beta\beta$ and to study neutrinos from both artificial and natural sources. Achieving these goals generally requires (i) scaled-up target procurement and radiopurity and purification capabilities; (ii) large area photosensor development with low-noise and low-radioactivity; (iii) high voltage and electric field capabilities compatible with multi-meter drifts and low-emission, large-area electrodes; and (iv) studying the effects and techniques for operating large doped noble liquid or gas detectors. The discovery capabilities of these detectors could be extended further by coupling them with a magnetic field, such to enable charge discrimination and improve momentum measurement.

7.8.4 Cross-cutting Challenges

In order to be sensitive to a wide range of physics phenomena, we must be able to make accurate and precise measurements of charge, light, or heat, from interactions of interest within our detectors, which requires in turn, a good understanding of the inherent noise levels, calibrations, and microphysics associated with these gaseous and liquid noble detectors. The challenges therein are cross-cutting, touching many different areas of experimental physics. But this also means that we can take a wider view to leverage facilities that will benefit many experiments across multiple frontiers. This deep understanding of the detection characteristics and calibrations will be essential components of preparing next-generation gaseous and liquid noble detectors for cutting-edge physics measurements in the Neutrino Physics Frontier, the Cosmic Frontier and the Rare Processes and Precision Measurements Frontier.

Flexible user facilities (not tied to any particular group nor experiment) play a key role in noble element R&D, both for calibration needs where in-situ measurements are insufficient and for short-term instrumentation tests where a permanent dedicated test stand is unnecessary. These facilities minimize duplication of efforts by providing community-wide resources to benefit multiple research efforts. Laboratory-scale facilities such as the Liquid Noble Test Facilities at FNAL and Stanford Linear Accelerator Laboratory (SLAC) serve a broad, unique and important role in service of the liquid noble detector development community, both lowering the cost of entry for developing new techniques and testing prototypes, and providing an excellent training ground for students and postdocs. In an era of increasingly large-scale experimental programs, these facilities and the efforts they support provide much needed opportunities for junior personnel to design and build whole experiments, while gaining valuable technical expertise from collaboration with the facilities' engineers and technical staff.

7.9 Radio Detection

Detection techniques at radio wavelengths play an important role in the future of astrophysics experiments. The radio detection of cosmic rays, neutrinos, and photons has emerged as the technology of choice at the highest energies. Cosmological surveys require the detection of radiation at mm wavelengths at thresholds down to the fundamental noise limit. A summary of the Snowmass Instrumentation Frontier's Topical Group on Radio Detection can be found in [47].

High energy astro-particle and neutrino detectors use large volumes of a naturally occurring suitable dielectric: the Earth's atmosphere and large volumes of cold ice as available in polar regions. The detection technology for radio detection of cosmic particles has matured in the past decade and is ready to move beyond prototyping or mid-scale applications. Instrumentation for radio detection has reached a maturity for science scale detectors. Radio detection provides competitive results in terms of the measurement of energy and direction and in particle identification when to compared to currently applied technologies for high-energy neutrinos when deployed in ice and for ultra-high-energy (UHE) cosmic rays, neutrinos, and photons when deployed in the atmosphere. It has significant advantages in terms of cost per detection station and ease of deployment.

IF10-1 While conceptual designs exist for next-generation arrays, investment in R&D can reduce cost and optimize designs.

IF10-2 Opportunities exist in optimizing for power and simplifying: e.g. by using ASIC-based digitizer and readout or RF System on Chip (RFSoC). Investigations are needed to identify synergies with experimental needs in other areas.

IF10-3 Remote power and communications approaches of very large extended arrays can still benefit from dedicated R&D. Explore synergies with experiments in other areas, like with the DUNE, SKA, and CTA experiments, which also need large distance communication and synchronization.

IF10-4 Enable future mm-wave cosmic probes through R&D and pathfinder experiments of new mm-wave detectors with higher channel density relative to current Cosmic Microwave Background (CMB) detectors.

7.9.1 Radio Detection of Cosmic Particles

Astrophysical neutrinos, cosmic rays, and gamma rays are excellent probes of astroparticle physics and HEP [48]. High-energy and UHE cosmic particles probe fundamental physics from the TeV-scale to the EeV-scale and beyond.

Radio detection offers opportunities to instrument large areas on the surface of the earth. This is important because at energies above an EeV, the cross section for neutrinos interacting with matter have increased so much that the detector area becomes a more important parameter for the acceptance than the fiducial volume. At these energies, the preferred conversion targets for the neutrinos are mountains, the earth's crust, ice, or even the atmosphere. For UHE cosmic rays and photons, radio detection utilizes the air shower formed in the atmosphere.

While the optical Cherenkov technique has been enormously successful in measuring neutrinos from $\mathcal{O}$(MeV) to $\mathcal{O}(10\,\mathrm{PeV})$, at higher energies, techniques at RF are the most promising for neutrino detection. In the energy range from 10 TeV to 30 PeV a factor of 5 in increase of sensitivity is needed in order to move from the discovery of cosmic neutrinos and the first correlation with sources to identify the sources of the cosmic neutrino flux and explore fundamental physics with high energy neutrinos.

Like in the optical, for radio techniques the two media being pursued broadly are the atmosphere and solid natural ice, the latter with emphasis on neutrinos. Both can be used to pursue science with cosmic rays, energetic neutrinos, or both. Above about 100 PeV, volumes of order $1000\,\mathrm{km}^3$, which can only be naturally occurring, are necessary to detect the rare astrophysical neutrino flux in this regime. Volumes of this scale are too large to instrument with the tens-of-km spacing necessary for optical sensors. This spacing of optical is set by the distance over which optical light is absorbed or scattered in the glacial ice that is used as the detection medium. However, clear ice is transparent to RF signals over distances of order 1 km, which sets the typical spacing for detectors using radio techniques.

There are many different approaches to the detection of cosmic particles at RF. These approaches, the instrumentation that is unique and common to each, and future developments are described in this section.

7.9.2 Askaryan

In matter, particle cascades induced by cosmic particles produce Askaryan emission. The emission comes about from the time evolution of a charge asymmetry that develops in these particle cascades by ionization electrons moving with the cascade's front and positive ions staying behind. It is coherent for frequencies up to about 1 GHz when viewed at the Cherenkov angle and is linearly polarized perpendicular to the cascade direction and inward to its axis. Askaryan emission was measured in test beam experiments in the 2000s. It

has also been observed to be emitted from cosmic ray air showers. Now, many experiments are searching for this signature from UHE neutrino interactions either from within the ice or by viewing ice from an altitude.

7.9.2.1 In-ice

One approach to detecting neutrinos via the Askaryan signature is by embedding antennas into the ice itself, and the first experiment to take this approach was RICE. Since then, ARIANNA, ARA, and RNO-G search for UHE neutrinos with antennas deployed in the ice, either at shallow depths (within ∼10 m of the surface) or somewhat deeper (up to 200 m). An integrated facility for a wide band neutrino detector is IceCube-Gen2 that will employ both optical and radio detectors. Deep detectors are employing interferometry-based trigger designs.

7.9.2.2 Balloon

Another approach to detecting the Askaryan signature from UHE neutrinos is to deploy antennas on a balloon-borne payload at stratospheric altitudes where the payload can view approximately 1.5 million km^2 of ice. At these altitudes, the threshold for a detection is higher, but above threshold, balloons greatly exceed ground-based approached in viewable area. The ANITA project flew four times under the long-duration balloon program of the National Aeronautics and Space Association (NASA), and the next-generation PUEO is set to launch in the 2024-2025 Austral summer season with a trigger that will use an interferometric approach.

7.9.3 Geomagnetic Emission

A cosmic ray incident on the atmosphere will produce a particle cascade, and charges in the cascade produce a transverse current due to the earth's magnetic field, which produces what is known as geomagnetic emission at RF. The geomagnetic emission is coherent up to frequencies of about 1 GHz and is linearly polarized perpendicular to both the earth's magnetic field and cascade direction. The Askaryan emission mentioned above also contributes to the RF signal from air showers on average at the 20-30 % level in energy density. The interplay between geomagnetic and Askaryan emission gives rise to a non-azimuthally symmetric signal pattern due to the interplay of the different radiation patterns. Both are collimated in a Cherenkov cone with an opening angle of typically a degree.

A next generation UHE cosmic particle observatory is required to exploit proton astronomy and to discover UHE neutrinos and photons. Such a next-generation cosmic particle observatory needs to cover a large area, up to 200,000 km^2. Radio detection is the current favorite to make deployment at this scale possible and the GRAND experiment was proposed to cover an area of this size.

7.9.3.1 Radio Detection of Cosmic Rays

In addition to the traditional strategies for detecting high energy cosmic rays incident on the atmosphere, which include detection of secondary particles, optical Cherenkov emission, and fluorescence emission, geomagnetic emission is a strategy that complements the others and has seen major advancements in the past two decades. Radio detection of cosmic rays has a round-the-clock duty cycle and leaves a broad ($\sim$ 100 m) footprint on the ground.

7.9.3.2 Detection of Neutrino-induced, Earth-skimming Air Showers

The combined geomagnetic and Askaryan signatures can also be used to detect air showers that can originate from energetic tau neutrinos that are earth skimming [49]. These can produce a tau lepton through a charged current interaction in matter, and the tau can subsequently decay to produce an EM or hadronic shower.

The detection of pulses consistent with air showers going in the upward direction has the advantage of being flavor sensitive, and has become an objective of many detectors. BEACON, currently in the prototype phase, TAROGE, and TAROGE-M are compact antenna arrays in elevated locations that aim to detect UHE ν_τ emerging upwards via the radio emission of the air showers that they trigger. ANITA and PUEO are also sensitive to upgoing ν_τ, from a higher elevation. GRAND is a planned experiment that will cover large areas with a sparse antenna array to detect the radio emission from air showers triggered by UHE ν_τ, cosmic rays, and gamma rays. This is also a neutrino signature for PUEO, the follow-up of ANITA, and many other dedicated projects instrumenting large areas with antennas such as GRAND or putting them in mountains such as BEACON and TAROGE.

7.9.4 Radio Detection and Ranging (RADAR)

An alternate strategy for detection of neutrinos at RF uses RADAR. When a high-energy neutrino interacts in the ice, it produces a relativistic cascade of charged particles that traverse the medium. As they progress, they ionize the medium, leaving behind a cloud of stationary charge. This cloud of charge, which persists for a few to tens of nanoseconds, is dense enough to reflect radio waves. Therefore, to detect a neutrino, a transmitter can illuminate a volume of dense material like ice, and if a neutrino interacts within this volume, the transmitted radio will be reflected from the ionization cloud to a distant receiver, which monitors the same illuminated volume.

With this technique, a custom signal is transmitted in the ice and received after reflections from neutrino-induced cascades. The experimenter can thus determine the properties of the signal (including the amplitude, up to what is permitted to be transmitted). Also, the RADAR method has excellent geometric acceptance relative to passive (Askaryan) methods, which require the detector to lie within a small angular window at the Cherenkov angle. Recent test beam measurements have demonstrated the feasibility of the method in the laboratory, with in-situ tests forthcoming. RET-CR will serve as a pathfinder experiment, and RET-N could enable radio detection of UHE neutrinos within the decade with the potential to complement or improve upon existing technologies in this energy regime.

7.9.5 KIDs

Cosmological surveys require the detection of radiation at mm wavelengths at thresholds down to the fundamental noise limit. The detection of mm-wave radiation is important for: studying cosmic acceleration (Dark Energy) and testing for deviations from general relativity expectations through measurements of the kinetic Sunyaev-Zeldovich effect, precision cosmology (sub-arcminute scales) and probing new physics through ultra-deep measurements of small-scale CMB anisotropy, and mm-wave spectroscopy to map out the distribution of cosmological structure at the largest scales and highest redshifts.

Imaging and polarimetry surveys at sub-arcminute scales will require $O(10^6)$ detectors over a $O(10\ \mathrm{deg}^2)$ fields-of-view (FoV) covering nine spectral bands from 30 GHz to 420 GHz. Spectroscopic surveys (over a smaller FoV initially, $O(1\,\mathrm{deg}^2)$, but potentially also reaching $O(10\,\mathrm{deg}^2)$) will require a further factor of 10–100 increase in detector count. The 2019 report of the DOE Basic Research Needs Study on HEP Detector Research and Development identified the need to carry out detector R&D to achieve this goal. The driver for new technology is not the detector count but the increased detector *density*. Whereas in current experiments, the detector packing density is limited by the physical size of elements in existing demonstrated multiplexing schemes, KIDs eliminate the need for additional cold multiplexing components, allowing for arrays at the densities needed for the science aims of proposed cosmological surveys.

KIDs are a technology that has gained significant traction in a wide range of applications across experimental astronomy over the last decade. A KID is a pair-breaking detector based on a superconducting thin-film microwave resonator, where the relative population of paired (Cooper pairs) and un-paired (quasiparticles) charge carriers govern the total complex conductivity of the superconductor. Photons with energy greater than the Cooper pair binding energy (2Δ) are able to create quasiparticle excitations and modify the conductivity. By lithographically patterning the film into a microwave resonator, this modification is sensed by monitoring the resonant frequency and quality factor of the resonator. Since each detector is formed from a microwave resonator with a unique resonant frequency, a large number of detectors can be read out without the need for additional cryogenic multiplexing components. In addition, the designs to be fabricated are relatively simple.

There are a number of KID-based architectures being developed for a variety of scientific applications. Direct Absorbing KIDs are the simplest variant, where the resonator geometry is optimized to act as an impedance-matched absorber to efficiently collect the incoming signal. To date, the only facility-grade KID-based instruments are based on this detector architecture, with the NIKA-2 experiment on the IRAM 30-meter telescope having demonstrated that the KID-based instruments are highly competitive with other approaches. Microstrip-coupled KIDs take advantage of recent advancements that allow for the ability to lithographically define circuits capable of on-chip signal processing with extremely low loss. The capability to robustly couple radiation from superconducting thin-film microstrip transmission lines into a KID with high optical efficiency is being developed. Thermal KIDs take a similar approach as has been developed for bolometric TES arrays. Instead of directly absorbed radiation breaking pairs, a thermally-mediated KID (TKID) uses the intrinsic temperature response of the superconducting film to monitor the temperature, and therefore absorbed power. It combines the multiplexing advantage of KIDs with the proven performance of bolometric designs in TES detectors, at the expense of fabrication complexity.

On-chip spectroscopy is a natural extension of multi-band imaging using on-chip filters to a filter-bank architecture to realize medium-resolution spectroscopic capability. Several approaches to on-chip spectroscopy exist at a range of technological readiness.

7.10 Cross-cutting Themes in Support of Detector R&D

The IF09 Topical Group has identified several cross-cutting themes that are crucial to address, as they affect almost all aspects of carrying out successful Detector R&D mentioned in the technical Topical Groups. They mostly deal with common infrastructure, such as detector facilities, access and to industry, workforce development and funding and collaborative models. The key findings are summarized here, while additional details are given further down.

IF09-1 Presently US funding for advanced detector R&D is institute-based rather than collaboration-based. Yet collaborations are more essential than ever to leadership in detector R&D technology.

To a significant extent, funding constraints have limited the opportunity to establish significant collaborative detector R&D programs. We recommend that funding for the DOE's KA25 Detector R&D program should be increased significantly (2x-5x) to enable the establishment of collaborative R&D programs that can address Grand Challenges and pursue blue-sky concepts.

IF09-2 Both, retention of key experts (institutional memory) and workforce development are critical to detector R&D. The recent "DOE traineeship in HEP instrumentation" is a step in the right direction and should continue. However, this focuses on the physicists while the instrumentation enterprise relies on a large set of uniquely skilled supporting players – mechanical and electrical engineers, composites designers and fabricators, device physicists, chemists, materials scientists and technicians. Development of the next generation of all of these experts is vital. We recommend that funding for key technical personnel essential to these capabilities be considered on equal footing with the physicists.

IF09-3 Innovative instrumentation research is one of the defining characteristics of the field of particle physics. Blue-sky developments in particle physics have often been of broader application and had immense societal benefit. It is essential that adequate resources be provided to support more speculative blue-sky R&D. One difficulty in the existing funding system is comparative review of incremental and blue-sky proposals. A separate funding opportunity and review process for blue-sky proposals could lead to more innovative R&D activity.

IF09-4 New R&D frameworks could enhance development: examples are the very successful CERN RD collaborations and the National Nuclear Security Administration's (NNSA) NA-20 consortia. LAPPD development was a HEP example that worked like that, but that has not been the detector R&D typical model. The ECFA detector roadmap recommended establishing six new RD Collaborations. The US should engage broadly and deeply to shape these global instrumentation RD collaborations. We recommend the US HEP community establish a robust collaborative research program that includes both participation in the international RD collaborations and establishing domestic detector R&D consortia.

IF09-5 Facilities (mainly at National Labs) are a vital element of detector technology development and should be supported. Present gaps that could be strengthened include: high-quality electron test beams, multi-TeV test beams, user access to low-temperature facilities covering liquid noble elements down to mK temperatures, low-noise - including vibration, RF, radioactive and cosmics - high-dose irradiation, and foundry access for radiation-hard microelectronics, semiconductor detectors, and superconducting devices for both development and production.

IF09-6 Multidisciplinary problems are prevalent in many areas of instrumentation development. The topic of multidisciplinary R&D was explored in the Snowmass MultiHEP 2020 workshop. Multidisciplinary work has funding, recruiting, and career development challenges that new R&D frameworks could alleviate.

IF09-7 Several themes that cut across multiple Instrumentation Frontier working groups were identified. The community should find ways to share expertise, tools, and developments in these areas: fast timing, cryogenic operation, and the need to solve challenging materials science and chemistry problems.

7.10.1 Facilities

The HEP detector instrumentation community depends on facilities and capabilities that are beyond the scale of the individual researchers' grasp. Those include test beam, irradiation facilities, cryogenic facilities, semiconductor foundry access, low-background and underground facilities, etc.

7.10.1.1 Calibration and Test Beam Facilities

Progress in particle physics depends on a multitude of unique facilities and capabilities that enable the advancement of detector technologies. Among these are test beams and irradiation facilities, which allow users to test the performance and lifetime of their detectors under realistic conditions. Test beam facilities are particularly important for collider and neutrino detector applications, while irradiation facilities are crucial for collider as well as some space-based astro particle detectors. It is important that the energy, intensity, particle composition and time structure of the beams are adequate for the detector needs for the next generation. In the area of irradiation facilities overlapping needs between detector and accelerator instrumentation as well as targetry development can be addressed.

To establish the global status of calibration and test beam facilities, the *Snowmass IF09 Test and Calibration Beams and Irradiation Facilities workshop* was held [50]. A summary of the workshop can be found in a Snowmass white paper [51] where we also develop the need and proposals for future facilities.

As summarized in the recent report on Basic Research Needs for HEP Detector Research and Development [1], future particle accelerator-based experiments will experience unprecedented radiation exposures of 10 GigaGray ionizing dose, and fluences of 10^{18} 1 MeV neq/cm^2 over their lifetimes. Detectors, support structures, electronics, data transmission components, and on-board data processing units will all need to be evaluated for performance at these dose rates and integrated doses two orders of magnitude greater than systems operating today. This will require new high-dose-rate environments for accelerated testing so that the anticipated integrated dose can be delivered in days rather than months or years. Activation of the detector materials will limit facility throughput unless remote material handling techniques are implemented. Such techniques are already employed for irradiation and post irradiation evaluation of accelerator components and for targets and windows for neutrino beam lines.

A broad array of test beam capabilities are also required to develop the next generation of detectors for tracking, calorimetry, and particle identification. In particular, access to beams of different particle species at a wide range of energies is critical to test the response and performance of different detector technologies, where well-calibrated instrumentation such as trigger hodoscopes, tracking telescopes, and Cherenkov detectors is often required to analyze and understand the performance of the device under test. Meanwhile, some of the capabilities being pursued for next-generation detectors place stringent demands on test beam time structure. For example, testing detector performance at high event rate and extreme (ps-scale) time resolution require test beams with high repetition rate and extremely short pulses, respectively. The BRN report calls for "a significant revitalization of US [test beam] facilities...to enable the detailed tests required" and highlights very precise test beams (in multiple dimensions – spatial, energy spread, timing, and intensity) as an important area where US-based facilities can play a world-leading role.

Meeting the needs of this diverse community motivates the support of a variety of test beams, with different features and capabilities, across the DOE complex as well as the use of international facilities. The white paper [51] surveys test-beam needs within the HEP instrumentation community and describes several opportunities for new facilities, improvements to existing test-beams, and detector test platforms that will provide essential and mutually complementary support for instrumentation development. Prospects include:

plans and applications for a high-intensity proton irradiation facility at FNAL; a new facility with improved infrastructure for test beam experiments at FNAL; a new multi-purpose electron beamline at SLAC capable of delivering high repetition rates and short pulses with precise, flexible timing for test beam applications; and the Water Cherenkov Test Experiment (WCTE) at CERN. Further into the future in anticipation of new accelerators at the high energy frontier multi-TeV test beams will be necessary.

7.10.1.2 Low-noise and Environmentally Stable Facilities

The particle physics community relies on a variety of specialized environmental conditions for operation of the most sensitive instrumentation. These include low-vibration and geologically quiet environments, low EM interference environments, low-radioactive background environments, and cryogenic environments to suppress thermal noise. Environmentally stable facilities, i.e. low vibration or low EM interference, tend to be very specialized for specific equipment (e.g. isolating a laser system or Nuclear Magnetic Resonance (NMR)) or to suppress specific frequency bands (seismic or EM) making it difficult to define the requirements for a general purpose user facility. In addition, these facilities are generally within the reach of individual research groups to establish locally as needed.

7.10.1.3 Cryogenic Test Facilities

Cryogenic test facilities are critical infrastructure for physics experiments in a variety of fields. Some notable examples include studying noble liquid properties for particle detection, low-temperature device development, and research in quantum information. The required technical knowledge and infrastructure capacity, including the cost of setting up and operating the test facilities, can place them out of reach of many individual research groups. As such, these research areas would greatly benefit from centralized user facilities. Cryogenic test facilities can require significant investments in infrastructure and ongoing operations costs, and warrant consideration of the development of national user facilities.

Several international institutions have established LAr test stands typically for specific purposes or experiments with limited measurement capabilities and access to the community. Some relatively large-sized facilities (more than 100 liters of LAr) include the ICARUS $\sim$ 50 liter LArTPC at CERN [52] with $\sim$ 250 liter LAr capacity, which is mainly used for ICARUS and DUNE detector electronics readout studies; the ArgonCube detector at University of Bern with $\sim$ 1100 liter LAr capacity, which is dedicated for pixel readout in LAr and DUNE's modular detector study; and the Integrated Cryostat and Electronics Built for Experimental Research Goals (ICEBERG) at FNAL with $\sim$ 3000 liter LAr capability, which is dedicated to DUNE cold electronics studies. As can be seen, these facilities are typically tied to the specific tasks that are not easily accessible as a user facility with the general purpose of R&D, such as testing new devices and detector designs, studying noble liquid property, calibrating detector signal response, or studying light detector performance, etc. The necessary initial components for a community LAr test facility include a large cryostat with sufficient volume and drift distance, adequate cryogenic infrastructure for condensing and gas circulation, a purification system to remove impurities with high electron attachment, a purity monitoring system with gas analyzers, basic high voltage system and readout electronics for TPC measurements, a photon detection system to study scintillation light, and the accompanying DAQ system.

The operation of sensors and systems at ultra-low temperatures is a major growth field, but one which necessarily has a high barrier for entry due to the relatively high cost of equipment, not just for the cooling platform itself but also associated measurement equipment and electronics and a knowledge gap in the operation and engineering of devices and systems at cryogenic temperatures. In addition, the typical fabrication, measurement and analysis cycle associated with the development of cryogenic devices will

often mean that test stands can be idle for considerable periods of time, making the economics of every PI or research group having dedicated research facilities economically unattractive. The establishment of a centralized facility would democratize the process of device development by allowing users access to test stands and measurement equipment for a variety of different tests, including but not limited to thermal, RF and low frequency tests. This is particularly valuable at the pre-proposal and proof-of-concept stages to validate new ideas before committing to full proposals or the expense of purchasing dedicated test equipment. In addition, such a facility would serve as a repository of knowledge of low temperature materials and other specialized information and offer a medium to connect researchers with specialized cryogenic engineering resources. Finally, such a facility is a vital tool for training a future workforce by providing hands-on experience in the operation of cryogenic systems and measurement equipment, typically outside the ability of a University level teaching laboratory to provide. Such a facility would necessarily consist of more than a single refrigerator test stand, since this is something that a well-equipped PI laboratory would be able to provide. Instead, it is envisaged that the proposed user facility would provide a suite of test stands available for different experiment types, including a number of test stands providing environments for the testing of specialized devices such as in underground and low-background environments, test stands with optical access, and stands incorporating magnetic fields. An initial set of capabilities for the facility would include DC and RF measurements with optional optical access and in the presence of a magnetic field or in a low-background (underground) environment. It should provide fast turnaround with minimal DC and RF screening capabilities as well as a platform for training of operators.

One facility that should be mentioned in this context is the Cryogenic Underground Test Facility (CUTE) at SNOLAB [53]. CUTE has already been used to validate performance of SNSPDs in a low-background setting, and many of its features seem to be addressing those needs described above. We would like to suggest the US HEP community to find ways to engage in this facility to the extent possible.

7.10.1.4 Semiconductor and Superconductor Foundry Access

HEP experiments rely on foundry access for production of custom sensors and electronics. Semiconducting sensors include silicon sensors (strips and pixels, MAPS etc.), CCD and CMOS imagers, and silicon and germanium bolometers. Superconducting sensors (TES, MKID, SNSPDs, etc.) are used as particle detectors, microwave sensors, and optical imaging arrays. Specialized HEP electronics typically take the form of ASICs, often operating in atypical environments including high radiation dose areas and at cryogenic temperatures, but also include devices incorporating superconducting materials (SQUIDS, qubits), and III-V semiconductors (e.g. high-electron-mobility transistor (HEMT) amplifiers). Looking further ahead, new processor technologies for on-board trigger and data acquisition for high-rate experiments may require purpose-built microelectronics. Access to foundry services has been essential for progress in detector development for HEP over the past three decades and will be increasingly important as channel density and rates increase and environmental conditions become more challenging.

By semiconductor foundry standards HEP is a small-volume, high-mix customer. One of the mainstays for access to foundries by the HEP community has been the Metal Oxide Semiconductor Implementation Service (MOSIS), operated by USC. MOSIS, founded in 1981, provides access to state-of-the-art (SOTA) and state-of-the-practice (SOTP) foundry processes at nodes from 500 nm down to 12 nm using multi-project wafer runs so that multiple parties can share the cost of mask sets and wafer processing during prototyping. It should be noted that while MOSIS provides good access to SOTA CMOS processes, it does not provide access to other important processes such as III-V, superconducting, specialty back-end-of-line processing such as back thinning and thin entrance windows, or integration (2.5D and 3D). In many cases "prototype" runs, which can produce 500-2000 die, are sufficient to support small to mid-sized HEP experiment needs. For larger experiments, a dedicated "engineering run" typically suffices.

The HEP community needs to maintain access to both SOTA and SOTP CMOS foundry processes. Access not only includes wafer processing, but access to design tools and data products – Intellectual Property (IP) blocks, Process Design Kits, device performance data etc. In addition to CMOS electronics, foundry access is needed for other silicon devices such as CCDs that require somewhat different processing. For CCDs Lawrence Berkeley National Laboratory (LBNL) and FNAL have successfully transferred the technology to a new commercial vendor, Microchip, to replace Teledyne DALSA when they elected to no longer produce these detectors. Working devices have also been produced with MIT-LL.

Very recently a disruptive access model with open-source, non-disclosure-agreement (NDA)-free ASIC prototyping has been spearheaded by the Google and the Skywater foundry. Multiple HEP groups are exploring this option for future development and further engagement and early adoption of open source design, where possible, should be encouraged. This is not only a potential way to reduce prototyping costs, but more importantly a way to involve physics students (as ooposed to specialized electrical engineering students) in ASIC design.

Potential synergies in the context of the recently passed CHIPS and Science Act [54] with the semiconductor detector program need to be explored in the near future.

Superconducting sensors are a key enabling technology for many HEP experiments with advances in sensor capabilities leading directly to expanded science reach. The unique materials and processes required for the fabrication of these sensors makes commercial sourcing impractical in comparison with semiconducting devices. Consequently, the development and fabrication of new sensors are often performed at academic clean rooms supported through HEP basic detector research and/or project funds. While this operational model has been successful to date, we are at a turning point in the history of superconducting electronics, as evidenced by the rapid growth in the field of quantum computing, when scale and sophistication of these sensors can lead to significant progress. In order to achieve this progress and meet the needs of the next generations of HEP experiments, it is necessary to broadly support all stages of the superconducting sensors development and to support a dedicated facility for this technology that is focused on HEP applications (with broader connections to non-HEP needs and industry).

7.10.1.5 TDAQ Facility

The creation of a dedicated (distributed) R&D facility that can be used to emulate detectors and TDAQ systems, offers opportunities for integration testing (including low- and high-level triggering, data readout, data aggregation and reduction, networking, and storage), and developing and maintaining an accessible knowledge-base that crosses experiment-project boundaries.

7.10.2 Synergies

7.10.2.1 Collaborative Research Models

The US HEP model for these has been to base facilities and core capabilities at National Labs as user facilities funded by KA25. Alternative approaches might be considered based on models such as the CERN RD research programs or the NNSA NA-20 research consortia. The CERN RD programs provide an organizational framework within which collaborative research is conducted, but provide no direct funding support. However, engagement in these RD programs often provides a strong argument for grant funding to support participation. In contract, the NA-20 research consortia are multi-year multi-institutional research

proposals with funding provided to the university groups and an expectation of support from National Labs already funded by the office. In both cases, the intent is to build 5+-year programs of research to address larger programmatic ambitions than individual institutions could tackle. The HEP investment in LAPPDs was to a large extent such a program.

Recently, both the DOE Instrumentation BRN [1] and the ECFA Detector Roadmap (2021) [37] noted the inherent value of the CERN RD collaborations to instrumentation R&D. The latter recommended the strengthening of existing RD collaborations and the creation of new ones in Calorimetry, Photo Sensors and PID, Liquid Detectors and Quantum Sensing. These RD collaborations are proposed to be global in extent and could be hosted by labs around the world. This plan has been approved by CERN Council and ECFA have been charged with its implementation over the next several years. We recommend the US HEP community engage broadly and early to help shape the global detector RD collaborations being established by ECFA and benefit from them.

Funding constraints in the US instrumentation R&D program limit the ability to establish detector R&D consortia. We recommend a significant increase in funding to enable DOE-HEP to establish a funding mechanism for collaborative or consortium funding. It should be understood that these research consortia will be multidisciplinary in nature and must include funding for scientists and engineers outside of physics.

7.10.2.2 Multidisciplinary Research

The topic of multidisciplinary R&D was explored in the MultiHEP 2020 workshop [55]. This consisted of a series of invited presentations and panel discussions to collect experience on successes, challenges, and lessons about multidisciplinary collaborations to further HEP R&D. The focus is on HEP developments that make use of expertise from outside HEP through collaborative efforts. R&D disciplines explored included chemistry, materials science, nuclear science, micro and nano fabrication. Examples included small efforts at universities, projects at National Labs, work with industry through the DOE's Small Business Innovation Research (SBIR) program and otherwise, long-term multi-institute development such as LAPPD, and agency experience. The workshop panel discussions identified relevant points in the categories working with other fields, working with industry, and multidisciplinary personnel and funding.

Working with Other Fields Development of new instrumentation is often only possible through expertise and capabilities from outside HEP. Examples at the workshop were LAPPD, barium tagging for $0\nu\beta\beta$ decay, use of carbon nanotubes for photon detection, etc. Informal discussions are required to establish the work scope for reasons summarized as "because you don't know what you don't know". Some interest in the HEP goals is more important than the expert's standing in the non-HEP field. The research philosophy is different in other fields. In HEP negative results are a success (most HEP results are negative), while other fields have narrowly defined goals and positive results are the measure of success. The publication approach is also different in other fields. There are no pre-prints since scoops are common and thus results remain secret until published. Publications are geared towards the next funding proposal. Author lists are small. It is a good idea to have agreements formalizing collaboration, funding, author lists etc. after the initial informal discussions.

Working with Industry There were numerous reports about successful SBIR efforts. The SBIR program offers a good path to fund multidisciplinary development by partnering with an appropriate firm. True partnerships between HEP scientists and firms are essential for success. An issue with SBIR is that many technologies critical for HEP do not have a lucrative commercialization path, but SBIR requires

commercialization as the end product of Phase 2. Even when commercialization is in principle possible, there is a large gap between Phase 2 and volume production for profit. It is difficult for small companies to bridge that gap.

Connecting with the right company is a challenge. Networking efforts can help. NP holds an annual exchange meeting for this purpose. Some National Labs have industry days, but not regularly or at the same level. BNL has a discovery park incubator.

For multidisciplinary work there may be co-founding opportunities. Each office has to allocate and spend the required SBIR levels and this leads to round-off errors because each office has to spend down an exact amount. This would allows NP to co-fund something with HEP, for example.

Multidisciplinary Personnel and Funding Very few institutes train people in multiple disciplines at once. It is therefore hard to recruit people to carry out multidisciplinary work. On the other hand, a student or postdoc developing in two disciplines at once may have a hard time finding the next job, because they will not be competitive in either one of these disciplines with peers who devoted themselves fully to it. They need to find a job where both disciplines are required. Funding agency offices tend to not like paying for personnel normally under other offices, which makes it hard to find multidisciplinary work with a single grant. Recent QIS and micrelectronics Funding Opportunity Announcements (FOA) have aimed at multidisciplinary work. Microelectronics has been more successful because (unusually) multiple offices co-funded the same FOA, while this was not the case for QIS, where each office had separate FOAs. More funding like microelectronics is needed if fostering multidisciplinary work is desired.

7.10.2.3 Co-Design Approach

Most past and current detectors were integrated as parts into the whole with assumptions about on- and off-detector communication and monitoring coming as either afterthoughts or as separate sub-system interface points. The complexity of the detectors for future experiments will require a more cooperative detector level co-design and co-development atmosphere. The community has the tools and repositories capable of creating and archiving an evolving detector design with sub-detector sections and interface documents created as functional blocks in separable areas with the hooks to create a coherent overview. An ideal system repository would hold representational blocks for fledgling sub-systems under development with interface documents that include target specifications such as data transmission protocols.

The full detector level framework for high-level simulation should be developed for each sub-system to participate in a functional simulation with abstracted performance parameters tuned using guidance from lower-level test bench simulations that are compatible with its internal design. In this way operational modes such as calibration, monitoring and data-taking, can be tested across system boundaries. This will help expose easy-to-ignore but important interface details that must be coherent across systems and can evolve to provide realistic latency and throughput for each sub-system that will be a basis for validation of intra-sub-system communication fidelity.

In the case of detector-specific simulation and reconstruction software, the tradition is that the detector and software design efforts are separate processes, with the latter dealt with as an afterthought. Consequently, suboptimal choices in terms of detector technology or configuration may lead to computationally expensive simulation and reconstruction algorithms, resulting in a longer publication turnaround time, physics results of lower quality, or the need to increase investment in computing resources. A collaboration model that includes the co-design of the detector and its software would allow to optimize physics performance simultaneously with the cost of hardware and computing [56].

7.10.3 Workforce Development for Instrumentation

The instrumentation workforce includes not only the physicists making the connections to the particle physics science mission, but the world-class scientists from other disciplines and the uniquely skilled technical staff that make the enterprise a success. Engaging with world-class scientists from other disciplines requires not only funding, but rewards and recognition commensurate with their contributions to the success of the HEP program. This extends to the technical staff without whom no major detector program could be realized. A summary of the topic can be found in [57].

There are two cultural hurdles that need to be addressed. The first is embracing scientists from other disciplines as equals. The second is the issue that both the scientists from other disciplines and the technical staff are funded primarily from soft funding streams (e.g. projects). This makes it very difficult to sustain staff expertise through lulls between major construction projects and makes these positions less attractive than comparable positions in industry that typically also come with greater financial compensation. Establishing a set of hard funding opportunities that allow for key technical positions to be funded as career opportunities could attract more highly qualified candidates for these vital roles.

7.10.4 Blue-sky Research and Tackling Grand Challenges in Instrumentation

Innovative instrumentation research is one of the defining characteristics of the field of particle physics. Blue-sky research is defined as highly innovative research that does not have a predefined application and is typically characterized by high risk and potentially high reward. In contrast, Grand Challenges have a defined goal but are transformational rather than incremental in nature. The Detector BRN defines a number of Grand Challenges for detector instrumentation.

In particle physics these R&D activities have often been of broader application and had immense societal benefit. Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science. It is essential that adequate resources be provided to support more speculative blue-sky R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics (discovering new physics may only be possible by developing novel technologies) and to society.

7.11 Summary

Advances in detector instrumentation enable advancements in HEP. The US has historically been among the leaders in the field in many areas of technologies. However, the shortage of the detector R&D program in the US has become evident, such as the opportunity for sustained careers in instrumentation, from student to tenured scientist or faculty, or the highly impactful CERN RD collaborations. Investments have to be made to close the gap in these areas and ensure that US HEP detector instrumentation will continue to be at the forefront of technological innovation and scientific breakthrough. The Snowmass Instrumentation Frontier has identified strategic R&D directions that would be beneficial to pursue within each of its Topical Groups. For a more detailed discussion we point the reader to the Topical Group reports. Furthermore, we have identified organizational and strategic needs that are common to a large part of detector technologies for HEP applications, such as common facilities, research consortia, funding models or multidisciplinary work. This process has also identified the need for regular funding opportunities for small-scale experiments,

which typically drive detector innovation on a much shorter timescale than the few mega-projects that comprise the majority of the HEP budget. Such innovation in turn benefits the entire program at large.

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8

Neutrino Frontier

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Executive Summary

Motivation

The discovery of neutrino mixing and oscillation, which implies that neutrinos have non-zero mass, was the first, and remains the only, laboratory demonstration of non-Standard Model physics. Neutrino mass requires the addition of new degrees of freedom — new interactions — to the Standard Model Lagrangian, but we do not yet know what form that will take or the profound impact it will have on particle physics. Over the past two decades, a successful and growing neutrino physics program has demonstrated unequivocally that neutrino mixing involves all three known flavors, has provided precision measurements of many of the parameters describing three-flavor neutrino mixing, and has greatly improved our understanding of neutrino properties and their interactions with matter. However, anomalous results have raised intriguing questions about the possibility of additional particles or interactions and our most fundamental questions about neutrinos remain unanswered. What is the origin of neutrino mass and why are neutrino masses so tiny compared to other Standard Model particles? Why is neutrino mixing so different from mixing in the quark sector? Is the three-flavor neutrino picture complete? The answers to these questions will lead to extensions of the Standard Model and are fundamentally linked to our understanding of the Universe.

The physics *of* neutrinos and the physics that can be done *with* neutrinos extends from sub-eV to EeV – across eighteen orders of magnitude – and touches nearly every other area of particle physics. Right-handed neutrinos, which are arguably the most minimal addition to the Standard Model that can accommodate neutrino masses, could be a portal to a potential dark sector. Many of the ideas about how to generate neutrino mass also address questions like the baryon asymmetry of the universe, or lead to new phenomena observable at current and future colliders, or predict rare processes like the lepton-number-violating neutrinoless double beta decay. It is still experimentally allowed for neutrinos to possess a wide range of surprising properties, including relatively large couplings to new (light) states, which would lead to observable effects in experiments. Oscillation of high-energy neutrinos traveling over very long distances can provide a critical test of our understanding of space-time. Neutrino oscillation, being a manifestation of quantum interference, is uniquely sensitive to tiny effects, like the phase difference caused by neutrino mass, and thus is used to look for new interactions or to test the foundations of quantum mechanics.

As a result of the weakness of weak interactions, neutrinos can also serve as messengers, carrying information about the physics taking place and the structures inside otherwise inaccessible systems such as the core of the Earth, the core of the Sun, supernovae, and active galactic nuclei. The information provided by neutrinos becomes even more valuable when combined with other data, e.g., from cosmic rays, gamma rays, and gravitational waves; neutrinos thus form a critical component of multi-messenger astronomy. Neutrinos can also be tools for more terrestrial concerns, such as nuclear nonproliferation.

The weakness of neutrino interactions and the smallness of their masses makes neutrino experiments particularly challenging, requiring bright sources and large, sensitive detectors. Over the past decade there has been an explosion of new techniques and technologies for producing and observing neutrinos. These technological developments will likely impact other fields directly – there are particularly strong synergies with dark matter detection – and they also imply that neutrino experiments are excellent tools for looking for non-neutrino physics beyond the Standard Model complementing other probes of beyond-the-standard-model (BSM) physics like collider experiments. Large neutrino detectors allow to put strong constraints on baryon-number-violating processes. Searches for very weakly coupled degrees of freedom, which may or may not have a direct connection to neutrino physics, will be performed at neutrino oscillation experiments and in dedicated experiments. Examples of such searches use existing machines, like the LHC, or future machines, like a muon collider, that lend themselves naturally to producing unique neutrino beams.

In the coming decade, the international high-energy physics community is committed to realizing next-generation neutrino oscillation experiments that will answer many of our remaining questions about neutrino oscillation, with a particular focus on CP violation and testing the three-flavor neutrino paradigm. These experiments also have the potential to discover additional physics beyond the Standard Model. The nuclear physics community is poisded to build at least two ton-scale neutrinoless double beta decay experiments that will explore the parameter space favored by the inverted mass ordering under the light neutrino exchange mechanism. Conceptual designs for upgrades and next-next-generation experiments with even broader physics scope and probing deeper into parameter space are being developed. There is remarkable diversity in the programs studying neutrino properties, using neutrinos as astrophysical messengers, and supporting the neutrino physics program with phenomenology studies, computing and algorithm developments, cross-section modeling and measurements, and detector and neutrino source R&D. The components of this broad program are all complementary and each is necessary to realize the promise neutrinos hold for deepening our understanding of the Universe.

Science Drivers

Many of the science drivers in neutrino physics derive from questions which arise directly from the discovery of neutrino oscillation and with it the realization that neutrino masses are non-zero. The community has made tremendous progress in addressing these questions, and as a result, the international landscape sports a rich portfolio of on-going experiments and construction of major new experiments [1]. The scientific questions motivating both the on-going program and the near-future program remain valid. Many fundamental questions remain about the values and nature of neutrino masses:

- **How are the masses ordered?** This is the question of whether the electron neutrino mostly is made up of the heaviest mass eigenstate or not. The answer directly informs models of neutrino mass generation and has important practical implications for absolute mass-scale searches as well as neutrinoless double beta decay. The current and near future program may provide the first indication of the answer to this question, which will be answered definitively by DUNE.
- **What are the neutrino masses?** The magnitude of neutrino mass will provide important information about the scale at which it is generated. Direct kinematic mass measurements provide a limit of around 0.8 eV, with the current program expected to eventually reach a sensitivity of 0.2 eV and longer-term efforts aiming for beyond that. Limits from cosmology are currently at the 0.1-0.5 eV level and the sensitivity will reach the 0.01 eV range over the next decade.
- **What is the origin of neutrino masses?** We currently have no good indication of the scale at which neutrino masses are generated and there is a wide variety of models for neutrino mass generation. These models admit many possibilities not available for the other fermions in the Standard Model. Related to this is the quest for a theory of flavor. Some of these mass and flavor models may lead to directly observable phenomena; some may not. Thus, a combination of circumstantial evidence provided by precision measurements and rare process searches across frontiers may aid in testing these models. Many models of flavor lead to correlations between observables and these correlations can be tested with precision measurements.
- **Are neutrinos their own antiparticles?** Without additional symmetries or interactions, neutrinos are likely to have a Majorana mass term, which would be unique among the fermions. A direct experimental consequence of a Majorana mass term would be neutrinoless double beta decay. The current experimental program is sensitive to half-lives of order 10^{26} years and the future ton-scale program could potentially probe the entire region allowed in the case of inverted mass ordering.

Beyond the immediate questions arising from the existence of neutrino mass, the study of neutrino properties allows us to address other major open issues:

- **Do neutrinos and antineutrinos oscillate differently?** The fact that the Universe consists of matter and not antimatter hints at a fundamental asymmetry between matter and antimatter, in the form of CP violation. We know that the known sources of CP violation via quark mixing and from the QCD Lagrangian are insufficient to account for the composition of the Universe. Neutrino oscillation is sensitive to one new CP phase and if neutrinos are Majorana particles, there are two additional neutrino-sector CP phases which may contribute to matter-antimatter asymmetry.
- **Is the three-flavor picture of neutrino mixing complete?** Precision measurements of neutrino oscillation in different channels and at different energies and baselines can be compared with each other and with predictions of three-flavor oscillation probabilities to determine whether the picture of

three-flavor oscillation is complete, or whether there is as-yet undiscovered physics impacting neutrino mixing and oscillation. The first signs of a breakdown of the three-flavor picture could be present in a number of so-called "anomalies," which are so-far unexplained experimental findings.

Our understanding of TeV-scale physics has seen a significant evolution with the advent of LHC results, and as a consequence the phase space for dark matter has exponentially increased. In particular, there is a renewed interest in looking for new states below the electroweak scale and for very small couplings to these new states:

- **Discovering new particles, interactions and the unknown** Neutrino properties are not as well constrained as those of the other known particles and thus admit new interactions at a strength comparable to their Standard Model interaction strength. They may also have unexpected properties. This in turn makes neutrinos a uniquely sensitive tool to probe the physics of a wide range of dark matter models as well as for generic searches for low-scale new physics. At the same time, neutrino experiments combine high luminosity sources of photons, nuclear and meson decays with very sensitive and large detectors. Neutrino experiments are thus discovery-class facilities for a wide range of models of BSM physics, many of which have been conceived only in view of recent LHC results.

Owing to current and future advances in detection capabilities, neutrinos can be used as a tool to study a wide variety of phenomena.

- **Neutrinos as astrophysical messengers** Neutrinos are the second most abundant known particle in the Universe – after photons – and play an important role in many astrophysical phenomena and cosmology. Studying neutrinos allows us to learn about a wide range of environments, like stellar fusion processes, supernova explosions, nucleosynthesis, and the origin of the highest-energy particles ever observed. Cosmology is sensitive to the number of neutrinos, the sum of their masses, and to potential new neutrino interactions. In return, the more precisely we can determine neutrino properties in the laboratory, the fewer degrees of freedom there are in fits to cosmological data.

All these science drivers need a supporting program of a broad and diverse nature, including applications for societal impact. Our current modeling of neutrino-nucleus interactions needs to be improved to fully exploit the precision physics program offered by future experiments. Improving it will require cooperation among experimentalists making new measurements; nuclear and particle theorists developing new models; computing professionals enabling the preservation and interoperability of the data, theory, and software tools. A better understanding of existing neutrino beams and novel neutrino sources also requires continued effort. Theory will clearly play a central role in neutrino science and is an integral part of the future program.

A new generation of neutrino detectors based on liquid and gaseous noble element time projection chambers presents a range of unprecedented computing challenges. These detectors produce very large data volumes whose character is distinct from collider data (very large events rather than very many events) and requires innovation in hardware and software. The on-going transition to a new computing paradigm with a much greater focus on heterogeneous computing resources (GPUs, FPGAs, etc.) based at high-performance computing facilities will require adaptation from experiments at all scales. However, it also presents opportunities, for example using advanced machine learning algorithms to address the challenge of reconstructing the high-resolution images produced by modern TPCs. Many neutrino experiments have specific performance requirements, e.g., low-energy particle detection or low background detectors, requiring

detector R&D. This R&D has strong synergy with technologies relevant for QIS; neutrino oscillation also provides a fertile test bed for our understanding of entanglement and other concepts in QIS.

Finally, underground facilities are needed by many experiments to reduce cosmogenic background. Design and management of these facilities requires a unique combination of expertise in mining, civil engineering, and science, and often involves collaboration with communities and commercial mines.

A common thread among the widely varying issues addressed by these programs is the need to collaborate across disciplines and sectors. Commitment to community engagement, including discourse with other scientific disciplines, a diverse and welcoming environment within HEP, and education and outreach, facilitates these necessary collaborations.

Breadth and Diversity of the Neutrino Program

The Neutrino Frontier includes a wide range of activities spanning the full range of scales, including DUNE as a major international program with more than a thousand collaborators; medium-scale experiments such as those making up the short-baseline neutrino program; contributions to international experiments; smaller-scale experiments at accelerators, reactors, and spallation neutron sources; down to tabletop experiments and blue-sky R&D activities. Many examples are described in the topical group reports and a comprehensive list of Neutrino Frontier experiments is provided in Tabs. 8-4-8-7, as well as a summary graphic in Fig. 8-1 created from information provided by community members.

All of these efforts have the potential to make paradigm-changing discoveries or innovations or provide necessary inputs to experiments that will make these discoveries, and they will work in synergy to address the science drivers described in Sec. 8. A program incorporating breadth and diversity of efforts at different scales does more than just increase the chances for major discoveries. Such a program is healthy for future scientific progress by making space for creative thinking, and also provides training opportunities to ensure a capable workforce in the long term. The last P5 report recommended: *"Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects"*. The Neutrino Frontier endorses continued and enhanced support of this recommendation.

Cross-pollination between Frontiers and other fields of science offers further opportunities. Physics topics within the Neutrino Frontier overlap strongly with each other, and also with other Frontiers. In areas where programs may have synergies, careful attention is merited to enable collaborative stewardship by traditionally separate entities. Examples include instrumentation for dark matter and neutrinoless double beta decay searches, which connects particle astrophysics, nuclear physics, and neutrino physics; the study of neutrino-nucleus interactions, which can probe nuclear structure as well as support measurements of neutrino properties; the detection of high-energy neutrinos with far-forward experiments at the LHC; and the Cosmic Frontier programs that provide insight into neutrino properties from cosmological observables. Also meriting attention are opportunities to make optimal use of national laboratories and international facilities for particle physics and other sciences, including those that have not historically hosted HEP experiments.

Building on Current Success

The U.S. has a strong ongoing neutrino program in pursuit of the science drivers identified in Section 8. Currently operating experimental programs are investigating anomalous results that may be early hints of

new physics, making increasingly precise observations of neutrino oscillation using neutrinos from a variety of natural and artificial sources, characterizing neutrino properties including the ways in which they interact with matter, participating in multi-messenger astronomy, and extending the energy range of astrophysical neutrino detection into new territory. Searches for neutrino mass using both direct kinematic methods as well as cosmological fits, together with advanced experiments pursuing neutrinoless double beta decay, are also a mainstay of the current and future portfolio. This program is supported and enabled by developing sophisticated accelerator, instrumentation, computation, and analysis techniques to facilitate increased precision of neutrino measurements.

The quest for the absolute mass of the neutrino has seen significant progress with tritium endpoint measurements. Eventually current experiments will probe masses as small as 0.2 eV. In the near future, sensitivity into the sub-0.1 eV range will come from cosmology and studies of large-scale structure. Over the next decade, sensitivities down to 0.01 eV are expected and thus the impact of neutrino mass on large-scale structure should be confirmed. At the same time there is active R&D and new ideas to extend the reach of direct kinematic laboratory-based mass searches by either looking toward electron-capture isotopes or by improving the source strength and energy resolution of experiments using tritium or other beta emitters. Some of these approaches may also make progress towards the most ambitious goal of detection of the cosmic background neutrinos originating from the Big Bang.

A number of successful efforts have led the way for next-generation experiments searching for neutrinoless double beta decay, which is the only near-term plausible way to answer the question of the Majorana vs. Dirac nature of the neutrino. The Department of Energy Office of Nuclear Physics is stewarding the next phase, at ton-scale, which will push limits down to the region consistent with inverted mass ordering, given the assumption of light neutrino exchange. Under this stewardship, at least two ton-scale experiments are planned, along with participation in international collaborations. Exciting possibilities exist for farther-future experiments beyond the ton scale with sensitivity to parameters allowed under the assumption of normal mass ordering. For full exploration of this physics program, and to enable robust discovery, multiple isotopes and multiple technologies will be needed.

A major recent experimental milestone was the unequivocal detection of ultra-high energy neutrinos of astrophysical origin by IceCube and the first detection of an extra-galactic source in 2018. Neutrinos propagate in straight lines, neither affected by magnetic fields nor absorbed by dust and thus are the ideal tool to find the origin of the highest energy cosmic rays; the data collected to date have disproven most models for the generation of the highest energy cosmic rays. Neutrinos are a major contributor to the enterprise of multi-messenger astronomy. Already now, the neutrinos detected by IceCube provide stringent bounds on neutrino properties and space-time structure. Other high-energy neutrino observatories in sea water and also using radio waves are being realized as well, expanding sky coverage and energy range. IceCube is currently undergoing the IceCube Upgrade which will pave the way to IceCube Generation 2, which will significantly extend the energy reach of the experiment. Together with DUNE and Hyper-K, IceCube also will push the study of atmospheric neutrinos to new levels of sensitivity especially in the search for BSM physics.

A plethora of on-going and planned experiments will probe neutrino properties like magnetic moments, existence of sterile neutrinos across a wide range of masses and mixing angles, neutrino-nucleus interactions, couplings to light new particles and many others. Some of these experiments use traditional particle physics methods, but others use tools from nuclear physics and astrophysics. We expect that the sheer breadth and diversity of the effort will be a continuing theme in neutrino science. Some of these experiments are motivated by a set of existing anomalies historically summarized under the theme of eV-scale sterile neutrinos. The experimental program going after these questions features accelerator-based approaches with stopped-meson, isotope decay at rest, and pion decay in flight as well as reactor neutrino experiments at a few-meter baselines. For the future, proposals for using radioactive sources produced either online or

offline are being pursued, as well as novel types of particle beams based on kaon or muon decays. Since its discovery in 2017, the study of coherent elastic neutrino nucleus scattering (CEvNS) has become available as a tool for the study of neutrino interactions with strong technology synergies with dark matter searches. Dark matter experiments eventually also will become sensitive to solar neutrinos and other natural neutrinos via CEvNS. There are also ideas for experiments with exciting low-energy astrophysical neutrino programs which could also serve as DUNE far detectors.

Currently operating long-baseline oscillation experiments have made significant observations of ν_e and $\overline{\nu}_e$ appearance and are making successful measurements of the parameters governing long-baseline oscillation. We anticipate that by the middle of the current decade there will be hints of answers to the question of the neutrino mass ordering and CP-violating asymmetry, although discovery-level measurements will not yet have been made. To accomplish this, significant progress has been made towards the next generation of oscillation experiments that are required to see this program through to its conclusion. JUNO will significantly improve the precision on a number of the neutrino mixing parameters and test the mass ordering with vacuum oscillation at the $3\,\sigma$ level; it is expected to come online in 2023. In the U.S., DUNE/LBNF was launched in response to the previous P5 as an international collaboration with goals of precisely measuring the parameters governing long-baseline neutrino oscillation. Construction of DUNE is underway after the very successful operation of prototype detectors and detailed simulation studies to validate and optimize its experimental design. DUNE is expected to begin taking physics data by 2029. Significant progress has been made on PIP-II, the upgrade to Fermilab's proton accelerator complex required for DUNE's neutrino beam, with conventional facilities nearing completion. Hyper-K is also proceeding in Japan with an experimental strategy for studying long-baseline neutrino oscillation that is complementary to that of DUNE. Hyper-K is expected to take data beginning in 2027.

At the completion of this next-generation experimental oscillation program, we expect to have measurements of all the neutrino mixing angles and mass differences at the few percent level or better, with the measurement of several parameters made in different channels. This will allow for a test of the unitarity of the mixing matrix, definitive determination of the neutrino mass ordering, and a measurement of the CP-violating phase with a resolution of 5-15 degrees (depending on its true value). This suite of measurements, in combination with searches for oscillation physics inconsistent with the three-neutrino paradigm, will address many of the outstanding questions related to the physics of neutrino mass. Additionally, future neutrino facilities enable a rich and diverse program of BSM physics probes. The combination of high-intensity proton beams and high-resolution detectors, along with the distance from the neutrino beam source to detectors, enable exploration of BSM physics parameter spaces highly complementary to BSM physics searches at Energy Frontier experiments.

DUNE is the largest project in the Neutrino Frontier portfolio and has been designed to definitively determine the neutrino mass ordering, measure the level of CP violation, and observe neutrino oscillation over a wide range of neutrino energies. These measurements represent a test of the completeness of the three-neutrino paradigm. DUNE also has a broad physics program beyond three-flavor oscillation physics that includes multi-messenger astronomy and astrophysics, searches for a wide variety of BSM signatures, and precision SM measurements.

DUNE and Hyper-K have very different detector designs that provide complementary input to our understanding of neutrino physics. DUNE's experimental design includes a baseline long enough to lift degeneracy between matter and CP-violating asymmetries, a high-power wideband neutrino beam covering a full oscillation period, liquid-argon-time-projection-chamber far-detector modules designed for detailed tracking of most final-state particles from neutrino interactions over a range of energies, and a near detector well matched to the systematics constraints needed for precision oscillation measurements. The Hyper-K experiment is based on a very large water Cherenkov detector, at a shorter baseline, in a high-power off-axis beam peaked at the first oscillation maximum. Therefore Hyper-K is optimized to collect a large

sample of beam neutrinos with a relatively narrow range of energies. Both strategies are expected to offer significant sensitivity to CP violation with very different systematics, baselines, and targets, which benefits our understanding of the underlying physics and will be especially powerful in disentangling the effects of potential new physics from three-flavor oscillation effects, as well as possible systematic effects. The experiments will collect highly complementary neutrino samples in the event of a core-collapse supernova, as DUNE is most sensitive to electron neutrinos via charged-current absorption while Hyper-K is most sensitive to antineutrinos via inverse beta decay on protons. The experiments have extremely broad and complementary physics portfolios that also include atmospheric and solar neutrinos, baryon number violation searches, and a vast array of searches for physics beyond the Standard Model. There are significant opportunities for collaboration and shared efforts benefiting both DUNE and Hyper-K, including US-Japan cooperation on accelerator and targetry issues; measurements, modeling, and analysis techniques to address the challenges of neutrino interaction physics; measurements and modeling of neutrino beams; and eventually joint analysis of the data, as is currently being pursued by NOvA and T2K.

DUNE is being built in two phases. Phase I is an initial experiment configuration consisting of two liquid argon far detector modules; a suite of near detector components suitable for the initial measurement program, including a movable LArTPC and a muon spectrometer, as well as an on-axis detector; and a 1.2 MW proton beam. Moreover, Phase I includes the far site infrastructure for four detector modules and all irreplaceable beamline components to support 2.4 MW beam operation. With the Phase I configuration, DUNE will be able to determine the neutrino mass ordering, make a measurement of the potentially CP-violating phase, and make improved measurements of other oscillation parameters, in addition to the broader program of astrophysics and BSM searches. In Phase II, to allow DUNE to achieve its full physics program, the third and fourth far detector modules will be added, the proton beam power will be upgraded to 2.4 MW, and the near detector will be upgraded to further constrain systematics for the precision oscillation measurement program. In the Phase II configuration, DUNE will make precision measurements that, in combination with each other and/or with world data, over-constrain the PMNS matrix to determine whether or not neutrino oscillation is well-described by the three-flavor paradigm. In the event that there are unknown particles or interactions impacting neutrino oscillation, these precision measurements will be the window for discovery. Each of the Phase II upgrade components also provides an opportunity to broaden DUNE's physics portfolio to address additional science drivers and to therefore involve a wider community, including potential opportunities for dark matter detection, neutrinoless double-beta decay measurements, and additional BSM searches. There is also significant community interest in other experimental efforts that may make use of Fermilab's upgraded proton accelerator complex.

DUNE is a world-class oscillation experiment hosted by the U.S. and LBNF is a unique facility offering many additional scientific opportunities to the international community, including the possibility of additional detectors at the near and far sites. Not only are LBNF/DUNE's science capabilities intrinsically unique and broad, but it will affirm our ability to act successfully in this role for a large high-energy physics facility. It will be important to demonstrate that the U.S. community and funding agencies can work together to create a long-term stable environment in order to enable international partners to commit to any future programs.

Outreach & Diversity, Equity, Inclusion

Among connections between the Neutrino Frontier with the other Frontiers, perhaps the most pervasive and vital are the connections with the Community Engagement Frontier, for which issues are shared with the entire Snowmass community. Given that neutrino physics represents a major component of the U.S. program, there are opportunities for leadership and special responsibility in addressing societal issues.

It is critical for the community to address issues of diversity, equity and inclusion. A work environment that is welcoming to all is both intrinsically desirable and conducive to scientific productivity. A strong outreach and education component to the program is crucial for attracting the best talent to the particle physics community as well as for communicating the impact of our science to the public. Neutrino physics facilities typically have a very significant impact on the surrounding communities, so it is important to be good citizens of them. Finally, neutrino physics has some specific practical applications of benefit to society, in particular for nuclear non-proliferation programs.

Neutrino Community Aspirations for US-HEP Neutrino Frontier Science and Activities

This section provides a concise high-level synthesis of input from the neutrino community regarding US-HEP planning. It is intended as input for the next P5, summarizing neutrino community aspirations for US-HEP activities in the next decade, with a view to beyond the next decade.

- Opportunities for advances in the neutrino sector are entwined with opportunities in many other sectors, spanning all of the Snowmass Frontiers and multiple scales of time, size and cost. **A future program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.** This process should also provide opportunities to explore and eventually resolve existing and future neutrino-related anomalies and to develop instrumentation and new beam technologies that will have a broad impact across the field. Furthermore, connections between programs should be carefully curated to optimize science output.
- There has been tremendous progress on oscillation physics with the current experiments and the DUNE/LBNF program since the last P5. However, the primary questions about the three-flavor paradigm remain unanswered, and the motivations for answering them, and probing new physics beyond the three-flavor paradigm, are undiminished. **Completion of existing experiments and execution of DUNE in its full scope are critical for addressing the NF science drivers**. Both Phase I and Phase II are part of the original DUNE design endorsed by the last P5. DUNE Phase I will be built in the current decade and DUNE Phase II (two additional far detector (FD) modules, a more capable near detector (ND), and use of the 2.4 MW beam power from the FNAL accelerator upgrade) is the priority for the 2030s.
- Existing technologies enable the original DUNE physics program for both Phase I and Phase II. However each piece of DUNE Phase II offers broader physics opportunities than originally envisioned. **To exploit these new opportunities, directed R&D needs to be supported.** These opportunities for DUNE Phase II should be explored with a process inclusive of the community at large.
- Many questions in neutrino physics arise from theory and conversely neutrino experimental results raise many theory questions. A strong neutrino theory program is therefore essential to reap the full scientific benefit from the investment into new experimental facilities. Moreover, there is a significant amount of theory understanding required to correctly connect experimental observables and simulations with the underlying physics parameters. **Strong and continued support for neutrino theory is needed.**
- Neutrinos have connections to practically all other sectors of particle physics as well as many adjacent disciplines, offering neutrino physicists the opportunity to be community leaders in issues of diversity,

equity and inclusion (DEI). These opportunities must be embraced. **The Neutrino Frontier has a special responsibility to contribute to leadership for a cohesive, HEP-wide strategic plan for DEI and community engagement.**

8.1 Introduction

This document represents a distillation of content generated by the extensive neutrino community activities since the beginning of the Snowmass process in spring of 2020.

The Neutrino Frontier is organized into ten Topical Groups, listed below.

- NF01: **Neutrino Oscillations.** Physics of neutrino oscillations in the three-flavor paradigm.
- NF02: **Understanding Experimental Neutrino Anomalies.** Sterile neutrino oscillations, including experiments or theoretical models on 3+1 and 3+N scenarios, as well as other conventional and BSM physics that can explain current short-baseline anomalies or alter disappearance/appearance neutrino oscillation probabilities.
- NF03: **Beyond the Standard Model.** Searches for signals from physics Beyond the Standard Model (BSM), both from a theoretical and experimental perspective.
- NF04: **Neutrinos from Natural Sources.** Neutrino detection from all natural sources, including the Sun, the Earth, and astrophysical sources.
- NF05: **Neutrino Properties.** "Anything about a neutrino," but especially: direct neutrino mass measurements, the Majorana-vs-Dirac nature of the neutrino, and electromagnetic properties of neutrinos.
- NF06: **Neutrino Interactions.** Neutrino interactions on a wide range of target nuclei and across the full spectrum of neutrino energies.
- NF07: **Applications.** Potential practical applications of neutrinos, including nuclear non-proliferation, geology, nuclear data, and applications of technology.
- NF08/TF11: **Theory of Neutrino Physics.** Theoretical aspects of neutrino physics. This is also a topical group within the Theory Frontier.
- NF09: **Artificial Neutrino Sources.** Development, characterization and understanding of human-made neutrino sources, including beams, reactors, and radioactive sources.
- NF10: **Neutrino Detectors.** Detector technologies capable of exploring neutrino physics across the full spectrum of possible energies, from sub-eV to EeV.

More detailed information relevant to each Topical Group area can be found in the respective reports.

The topics considered within these topical groups overlap between groups to a very large extent. Furthermore, there are significant overlaps with *all* of the other Snowmass Frontiers, perhaps most notably with the Cosmic Frontier, the Theory Frontier and the Instrumentation Frontier.

The content in this report draws heavily on executive summaries of the ten Neutrino Frontier topical group reports. However, we are not organizing the material in this report exactly along the lines of the topical

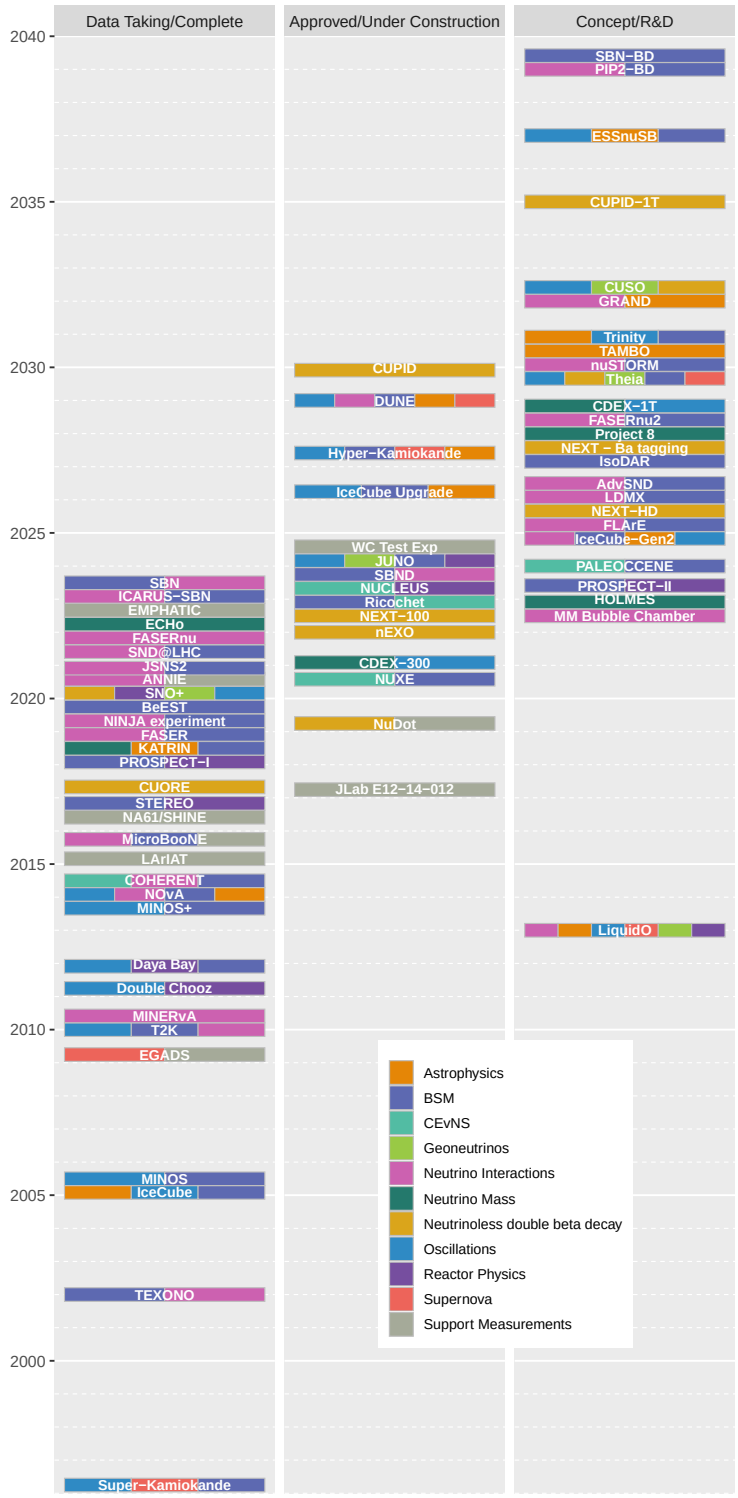

Figure 8-1. *Summary plot of experiments indicating rough time scale and range of physics topics addressed by each. The information is provided by the collaborations. Details and references are found in Tabs. 8-4-8-7.*

group material, given the many overlaps between topics. Citations for experimental programs are for the most part omitted, with the exception of some references to Snowmass contributions ("white papers") submitted to the Neutrino Frontier. However a full listing of experiments, including references, provided by the community, can be found in Tabs. 8-4-8-7.

8.1.1 Neutrino Frontier Activities

Below is a brief summary of the community process within the Neutrino Frontier. Materials can be found at `https://indico.fnal.gov/category/1101/`.

- April 2020: Topical groups formed.
- July 2020: Neutrino Town Hall session for initial community input. Input from this meeting resulted in the formation of a TF11 topical group to represent neutrino physics within the Theory Frontier. The new group retained an identity within the Neutrino Frontier as NF08.
- August 2020: 311 Snowmass Letters of Interest received by the Neutrino Frontier.
- Fall 2020: several topical workshops held (some continuing after the pause).
- First half of 2021: Snowmass pause.
- Fall 2021: "Neutrino Frontier White Paper Coordination Workshops." Mini-workshops designed for community members to present and discuss the content of their contributions held.
- Jan-Feb 2022: Topical group feedback meetings held to get community input on topical group report drafts.
- March 2022 Hybrid Neutrino Frontier meeting at Oak Ridge National Laboratory held. Neutrino Frontier report executive summary content developed.
- March-April 2022: Snowmass Neutrino Colloquia: four sessions of three talks each held to communicate main neutrino concepts and issues to the broader Snowmass community.
- July 2022: Community Summer Study in Seattle.

Overall 86 Snowmass contributions ("white papers") were submitted to the Neutrino Frontier. Report drafts were opened for several rounds of feedback. We benefited greatly from the consistent and deep engagement of the community in this process.

8.2 Physics Topics

In this section, we will summarize the main physics questions within the Neutrino Frontier and strategies for addressing them.

8.2.1 Theory and Motivation

The discovery of nonzero neutrino masses requires new fundamental fields and new interactions. We know very little about this new physics other than the fact that it exists. The new degrees of freedom can be fermions or bosons, ultra-light or super-heavy, charged or neutral, within reach of experimental efforts being pursued today or virtually invisible to any foreseeable future experiment. At the same time, the discovery of a new mixing matrix – very different from the quark one – serves as a new, perhaps decisive, piece to the elusive flavor puzzle.

A robust neutrino theory and phenomenology effort is required in order to exploit the unique probes of fundamental physics offered by neutrino experiments – to interpret the data, build models to accommodate new phenomena, provide guidance for future experimental efforts, and connect the new discoveries in neutrino physics to other areas of particle and nuclear physics, astrophysics, and cosmology. Neutrino theory requires a broad set of tools in order to attack a unique set of physics problems. Here we highlight the role and the goals of neutrino theory, concentrating on how it complements and contributes to theoretical efforts in other areas of fundamental physics, and on some of the challenges for the near future and the coming decades.

Among the goals of neutrino theory is to identify the different hypothetical degrees of freedom and interactions responsible for nonzero neutrino masses. More progress requires a coherent theoretical and phenomenological effort to establish connections to other outstanding questions in fundamental particle physics ranging from quantum gravity to the mechanism of baryogenesis to the dark matter puzzle. On the phenomenology side, the physics behind nonzero neutrino masses can manifest itself in, to name a few, neutrino oscillations, fundamental electric-dipole moments, the $g-2$ of charged fermions, charged-lepton flavor violating processes, or high energy colliders. Theory is required in order to explore these connections and identify promising new directions.

The flavor puzzle – understanding the underlying fundamental physics that is responsible for the patterns observed in the quark and lepton masses and mixing parameters – is also the subject of theoretical physics research. It may prove to be one way in which ingredients of a more fundamental theory of nature, including string theory, manifests itself, and it may contain information associated with grand unification. The fact we do not yet have all the pieces of the lepton mixing matrix in place allows one to test different general principles that may lurk behind lepton masses and mixing. Expectations from theories of flavor help provide guidance regarding how well we should measure mixing and other fundamental parameters.

In the three-flavor picture, all three mixing angles and two mass-squared differences have been measured, and improved precision is required for further progress. In order to fully exploit data from long-baseline oscillation experiments, our quantitative understanding of neutrino scattering cross sections must improve significantly. Furthermore, since neutrinos only interact weakly and the values of neutrino oscillation parameters are such that for terrestrial experimental setups one is forced to work with neutrino energies below a few GeV, one needs to understand the scattering cross section of neutrinos off complex nuclei, including carbon, oxygen, and argon. Theoretical nuclear physics is required in order to properly describe the targets and the medium through which the products of the collision propagate. A precise description of relatively low-energy neutrino–nucleon scattering depends on the tools of lattice gauge theory. At lower energies, the physics of coherent elastic neutrino-nucleus scattering, first observed a few years ago, needs input from theoretical nuclear physics. On the other end of the energy spectrum, in order to fully exploit the physics of ultra-high-energy cosmic neutrinos, a solid theoretical understanding of neutrino deep-inelastic scattering is required.

On the more phenomenological side, neutrino theorists explore, very broadly, the physics potential of long-baseline and short-baseline neutrino oscillation experiments. Phenomenological work has revealed, in the last few years, that experimental setups aimed at precisely measuring oscillations can be used to look for relatively light, new degrees of freedom, including candidates for the dark matter and new fermions that may have something to do with nonzero neutrino masses. This type of work serves as motivation for exploring different options for near-detector complexes and informs decisions regarding promising new detector technologies. Phenomenological and model-building efforts are also required in order to interpret neutrino oscillation data, including current and any future anomalies. In particle physics experiments, in order to fully exploit experimental data, a coherent experimental-phenomenological-model-building effort is required. Neutrino experiments in general, and neutrino oscillation experiments in particular, are no exception.

Searches for the violation of lepton number inform fundamental neutrino physics and are motivated by neutrino theory in different ways. Different theoretical efforts are required in order to connect lepton-number-violating observables to neutrino properties and other new physics, and in order to connect different lepton-number-violating phenomena to one another. The deepest probe of the violation of lepton number is the search for neutrinoless double-beta decay ($0\nu\beta\beta$). The relation between the lifetime of $0\nu\beta\beta$ and fundamental physics parameters requires precise inputs from theoretical nuclear physics and nucleon physics. Current efforts combine state-of-the-art tools from lattice gauge theory, capable of estimating nucleon-level processes, with those of nuclear physics, that define the nontrivial state of these nucleons inside of the complex nuclei of interest.

Neutrinos are also produced in intense astrophysics environments and, together with photons and gravitational waves, serve as messengers between us and the cosmos. Thanks to the weak-interaction nature of neutrino scattering and the very long neutrino lifetime, these neutrinos can and have been detected on Earth, allowing, with nontrivial input from theory, one to learn more about the different astrophysical processes and the properties of the neutrinos themselves. The detection of neutrinos from core-collapse supernova explosions, in particular, provides invaluable information about these violent phenomena, but these data require significant input from theory in physics and astrophysics to interpret. Incorporating neutrino-flavor information requires understanding the very challenging physics of flavor-transport inside the explosion.

At higher energies, neutrinos from the cosmos have been detected with energies between 1 TeV and 10 PeV. These observations are expected to shed light, with necessary help from astrophysics and astro-particle theory, on the cosmic ray puzzle and the ultimate particle accelerators in the universe. Ultra-high-energy neutrinos are also unique probes of new phenomena and have been explored extensively by the phenomenology community. Their very long travel distances and extreme energies are sensitive to neutrino properties, including the neutrino lifetime, and, assuming one can distinguish neutrino flavors, allow for powerful tests of the Lorentz invariance and the unitary evolution of quantum mechanical states.

At the opposite end of the energy spectrum lie the cosmic neutrinos produced at the Big Bang. These have never been directly observed but influence the evolution of the Universe, including the formation of structure. Their existence has been robustly inferred through a variety of different probes, including measurements of the primordial abundances of light nuclei (deuterium, helium, lithium) and precision measurements of the properties of the cosmic microwave background. Theory and phenomenology are required in order to compute the impact of primordial neutrinos and extract, from diverse measurements of the large-scale structure of the Universe, neutrino properties. Some of these translate into nontrivial theoretical and computational physics problems involving many-body physics, nonlinear dynamics, etc. New neutrino properties may be responsible for some of the observed discrepancies in cosmological data, including the H_0 puzzle. The exploration of these new properties – how they impact cosmic surveys, how

they can be constrained by Earth-bound experiments – is the job of particle and astroparticle theorists and cosmologists.

In the last decade, the neutrino theory effort has grown both in the United States and in the rest of the world, but so has the need for a more robust domestic theoretical physics community. Some positive developments include a few dedicated efforts from the Department of Energy and the National Science Foundation, increased investment in neutrino theory in the national laboratories, and a more robust "neutrino" footprint in the lattice [2] and nuclear physics communities. These are necessary but not sufficient; the domestic neutrino theory community is still very small. A dedicated and coherent effort, with significant investment from the funding agencies, enthusiastic commitment and leadership from the present neutrino theory community, and the support of the wider particle theory and neutrino experimental communities is absolutely necessary. To meet the proposed experimental schedules and ambitions, such an increase in the neutrino theory effort is needed now.

8.2.2 Three-Flavor Neutrino Oscillation

8.2.2.1 Goals in Three-Flavor Oscillations

Understanding the flavor structure of particle physics, why the fermion masses are distributed as they are and why their mixing with the weak interaction has the structure it has, represents one of the biggest gaps in understanding of our model of particle physics. Neutrino oscillation measurements of the remaining unknowns, the neutrino mass ordering, the octant of θ_{23}, and the value of $\delta_{\rm CP}$, will enhance our knowledge of the three-family structure of particle physics. Furthermore, precise measurements of the three-flavor oscillation parameters will allow consistency tests of the three-flavor paradigm which could lead to discovery of additional new physics.

Thanks to the many oscillation experiments over the last several decades, a clear picture of the overall framework of three-flavor oscillations has emerged. We have two mass-squared differences: Δm^2_{21} and Δm^2_{31}, the magnitudes of which are well measured. We know two of the mixing angles – θ_{13} and θ_{12} – fairly well. The measured value of the third mixing angle – θ_{23} – is consistent with maximal, but with insufficient precision to determine its octant if non-maximal, and the complex phase $\delta_{\rm CP}$ is largely unconstrained. The three primary goals of the coming years of neutrino oscillation measurements are:

1. to determine the "neutrino mass ordering," which is defined by the sign of Δm^2_{31},

2. to determine whether θ_{23} is more than or less than 45° and how close to maximal it is, known as the "octant" question, and

3. to measure $\delta_{\rm CP}$ and determine if $\sin\delta_{\rm CP} = 0$ can be excluded or not.

Some of these parameters can be assessed at an individual experiment (with input from orthogonal experiments), and some parameters will first be measured as a result of global analyses of all relevant neutrino data, known as global fits. Tau neutrino appearance [3] can further over-constrain the picture of neutrino mixing.

8.2.2.2 Facilities for Three-Flavor Oscillations

Facilities for measurements of three-flavor oscillation parameters include JUNO, Fermilab/SURF [4–6], J-PARC/Kamioka [7], IceCube/DeepCore, and KM3NeT, with technically diverse characteristics. Current-generation experiments each have some sensitivity to the three primary oscillation physics goals, but are unlikely to reach the required statistical thresholds for definitive determinations. Next-generation experiments are expected to provide definitive answers to these questions for most of the three-flavor parameter space. The broad experimental program reflects the fact that there are many parameters in the three-flavor oscillation picture with partially degenerate effects on oscillation observables, such that multiple experiments measuring the same parameter via different oscillation channels and experimental techniques are highly desirable to disentangle three-flavor effects and check the completeness of the three-flavor paradigm.

There are currently two operating long-baseline experiments: NOvA in Minnesota with a beam from Fermilab [8], and T2K at Kamioka with a beam from J-PARC. Both measure ν_μ disappearance and ν_e appearance in a narrow-band neutrino beam. NOvA measures neutrinos from the NuMI beam using functionally identical segmented liquid scintillator detectors located onsite at Fermilab and at a baseline of 810 km, in northern Minnesota. T2K measures neutrinos from the J-PARC beam using a suite of near detectors and the Super-Kamiokande water Cherenkov detector as the far detector at a baseline of 295 km. T2K and NOvA have been taking data since 2009 and 2014, respectively, have observed ν_e and $\overline{\nu}_e$ appearance and have published measurements of Δm^2_{32}, $\sin^2 2\theta_{23}$, and $\delta_{\rm CP}$. Figure 8-2 shows a comparison of the best-fit values for $\sin^2 2\theta_{23}$ and $\delta_{\rm CP}$ for the two experiments, using external data to constrain $\sin^2 2\theta_{13}$. T2K sees a relatively large asymmetry in $\nu_\mu \to \nu_e$ vs. $\overline{\nu}_\mu \to \overline{\nu}_e$, thus favoring CP-violating values of $\delta_{\rm CP}$, while NOvA does not see such an asymmetry, resulting in a slight tension between the experiments [8]. A joint fit for oscillations is being undertaken by the two collaborations.

Both experiments plan to continue taking data into the mid 2020s. For the most favorable parameters, NOvA expects up to 4σ sensitivity to the neutrino mass ordering and T2K expects in the most optimistic case $> 3\sigma$ sensitivity to CP violation. The actual sensitivity for both experiments is, however, highly dependent on the true values of the oscillation parameters, and it is not expected that this current generation of experiments will be able to provide definitive answers to the primary questions in the Neutrino Frontier.

Both Fermilab and J-PARC/Kamioka plan to host next-generation neutrino experiments with the goal of definitively addressing the three open questions in neutrino oscillation. DUNE [9] is the next step in the evolution of the Fermilab program. The DUNE collaboration was formed to realize the 2014 P5 vision of a best-in-class long-baseline experiment based at Fermilab. As the next-generation underground water Cherenkov detector in Japan, Hyper-Kamiokande (HK) [10] builds on the highly successful Super-Kamiokande and T2K experiments.

DUNE is designed to achieve its physics goals by pushing both the intensity and precision beyond what is achieved by current long-baseline neutrino oscillation experiments. Key features of this design include a high-power beam, a broad neutrino spectrum to measure the shape of the oscillation pattern, a long baseline of ∼1300 km, large far detectors located deep underground using liquid argon technology for particle identification and energy measurement, and an optimized near detector [11] with the same technology as the far detector to constrain systematics and enable a broad physics program. Critical components of the near detector are movable, to facilitate collection of data at multiple off-axis angles, which will reduce sensitivity to neutrino interaction modeling, a critical source of systematic uncertainty for long-baseline analyses; this capability is referred to as DUNE-PRISM [11]. DUNE's long baseline provides excellent sensitivity to the matter effect on neutrino oscillations and hence strong resolving power for the neutrino mass ordering. DUNE will be able to make precise measurements of Δm^2_{32}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, and $\delta_{\rm CP}$. Figure 8-3 shows the ultimate DUNE sensitivity to these parameters after several exposures. It is interesting to note that

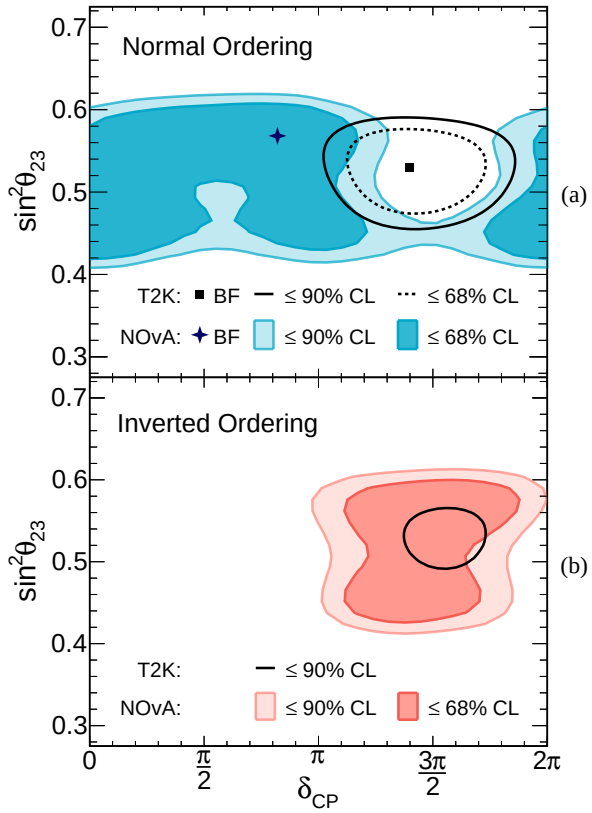

Figure 8-2. *The best-fit values of* $\sin^2\theta_{23}$ *and* $\delta_{\rm CP}$ *to NOvA and T2K data for the normal neutrino mass ordering (top), and the inverted neutrino mass ordering (bottom) [8].*

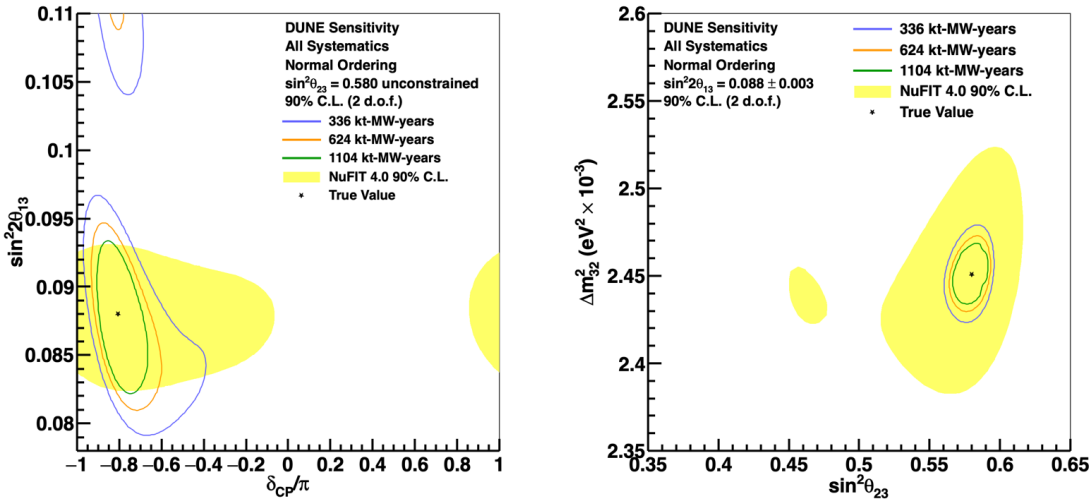

Figure 8-3. *90% confidence intervals for* $\sin^2 2\theta_{13} - \delta_{\rm CP}$ *(left), and* $\sin^2 23 - \Delta m^2_{32}$ *(right) after a range of exposures in kt-MW-years, for a projected measurement with assumed true parameter values near the current global best fit. Yellow regions indicate recent global fits from NuFIT 4.0.*

DUNE sensitivity to $\sin^2 2\theta_{13}$ will ultimately be comparable to that from reactor experiments, allowing a unitarity test of the PMNS matrix.

As a result of resource limitations on the LBNF and DUNE projects, DUNE will be built in two phases, detailed in Table 8-1. The highest priority is to deliver the full LBNF facility, including far site conventional facilities to accommodate four 17-kt FD (each at least 10-kt fiducial) modules, near site conventional facilities to support the full ND, and a 1.2 MW beam that can be upgraded to 2.4 MW. LBNF will be completed before the beginning of DUNE Phase I data-taking in the late 2020s. The Phase I configuration, consisting of the first half of the required far detector mass, half of the required beam power, and the minimal suite of ND components required to make credible oscillation physics measurements, is sufficient for early physics goals, including the determination of the neutrino mass ordering. However, Phase II is required to achieve the precision neutrino oscillation physics goals laid out by the last P5. Phase II, which completes the full DUNE scope, and includes upgrades to at least 40-kt of far detector fiducial mass, a 2.4 MW proton beam, and the full near detector, is critical for both the oscillation and non-oscillation physics programs of DUNE. Additionally, each of the Phase II upgrade components also provides an opportunity to broaden DUNE's physics portfolio to address additional science drivers and to therefore involve a wider community, including potential opportunities for dark matter detection, neutrinoless double-beta decay measurements [12], and additional BSM searches. There is also significant community interest in other experimental efforts that may make use of Fermilab's upgraded proton accelerator complex [13].

Parameter	Phase I	Phase II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	2.4 MW	FD statistics
ND config	ND-LAr,TMS, SAND	TMS → ND-GAr [14]	Syst. constraints

Table 8-1. *A description of the two-phased approach to DUNE. ND-LAr, including the PRISM movement capability, and SAND are present in both phases of the ND. TMS: Temporary Muon Spectrometer. SAND: System for on-Axis Neutrino Detection.*

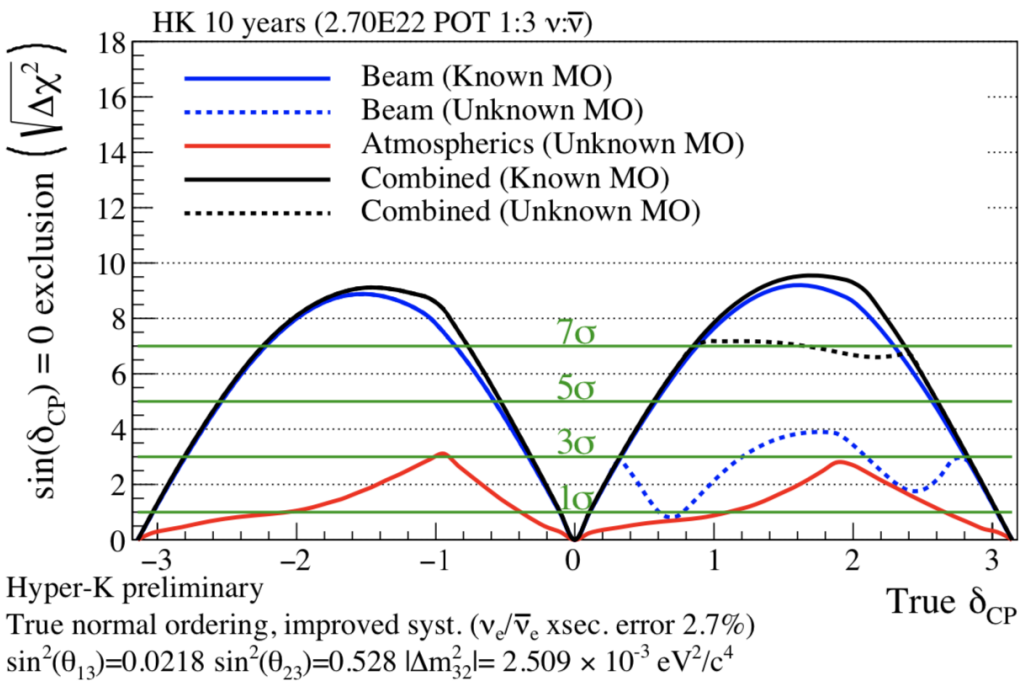

Figure 8-4. *HK sensitivity to exclude* $\sin\delta(cp) = 0$*, plotted as a function of the true value of* $\delta_{\rm CP}$*, assuming the mass ordering is unknown. A combined fit of HK beam and atmospheric neutrinos significantly enhances the HK sensitivity to* $\delta_{\rm CP}$*.*

The HK experiment plans to utilize the upgraded J-PARC 1.3 MW proton beam, an upgraded near detector, a proposed new intermediate detector to be installed ∼1 km away from the neutrino production target, and a new 260 kt far detector located 295 km away from the neutrino source near Super-K. The new intermediate detector would allow for measurements at a range of off-axis angles for use in a PRISM analysis. As shown in Figure 8-4, HK will have strong sensitivity to CP violation for much of parameter space, assuming the neutrino mass ordering is known. While HK's design parameters will make mass ordering determination difficult using its accelerator neutrino sample alone, a simultaneous fit to accelerator and atmospheric neutrinos is expected to significantly enhance sensitivity to oscillation parameters. As in DUNE, excellent control of systematic uncertainties is critical, with significant improvements in sensitivity possible if systematics are reduced relative to current T2K levels. In addition to the accelerator and atmopheric neutrino samples discussed here, HK will also be sensitive to a broad array of physics processes, including nucleon decay, solar neutrinos, supernova burst neutrinos, and diffuse supernova background neutrinos, with significant sensitivity to physics beyond the standard model. Civil construction for the HK tank is underway, with data taking scheduled to start in 2027.

JUNO (Jiangmen Underground Neutrino Observatory) is a large liquid scintillator detector in South China. JUNO projects measurements of $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{32} with resolutions $\sim \pm 1\%$ in six years of data taking, using reactor antineutrinos from two commercial power plants, detected via inverse beta decay. If JUNO can achieve the goal energy resolution of $\pm 3\%$, the question of the neutrino mass ordering can be resolved at 3σ by observing the phase of the "fast" oscillation from Δm^2_{32} superimposed on the "slow" oscillations due to Δm^2_{21} in the recoil electron energy spectrum. JUNO anticipates that data collection will begin in 2023.

IceCube can observe atmospheric neutrinos in a very wide energy range, from the order of GeV to 100 TeV. The IceCube Upgrade improves the resolution of neutrino energy and direction and lowers the energy threshold, allowing for improved neutrino oscillation sensitivity in atmospheric neutrinos. In particular, the measurement of the matter effect of atmospheric neutrinos by IceCube Upgrade, combined with the JUNO experiment, has significant sensitivity to the neutrino mass ordering. Atmospheric neutrinos, particularly in the high-energy region, are also well suited for searching for physics beyond the standard model.

8.2.2.3 Supporting Measurements and Capabilities

Auxiliary measurements, particularly hadron production measurements to constrain neutrino fluxes and flux systematic errors, as well as precision measurements of cross-sections to constrain interaction-model systematic errors, are necessary for precision three-flavor oscillation measurements. Some of these essential measurements are described in Sections 8.2.6 and 8.3.2.1 in this document and in more detail in reports from NF06 (Neutrino Interaction Cross Sections) [15] and NF09 (Artificial Neutrino Sources) [16].

8.2.3 Physics Beyond the Standard Model in Neutrinos and Neutrino Experiments

The arrival of the "precision era" in neutrino physics comes with both challenges and opportunities. One of these opportunities is the ability to search for evidence of or to discover BSM physics, expanding the physics scope of current and future experiments well beyond the measurement of three-flavor neutrino oscillations. In fact, while the SM describes with great accuracy most of the phenomena observed in high-energy physics, a number of fundamental scientific questions still need to be answered:

1. What are the properties and interactions of neutrinos, and how many neutrinos are there? What is the explanation behind the observed anomalies in short-baseline neutrino experiments?

2. What is the mechanism responsible of neutrino mass generation? Are lepton and baryon numbers fundamentally conserved, or just accidental symmetries?

3. What is the mechanism responsible for the matter-antimatter asymmetry of the Universe?

4. Is the dark sector as complex and phenomenologically rich as the visible sector? How does the dark sector interact with the visible sector?

5. Do all the forces unify? If so, at what energy scale?

Current and future neutrino experiments are in an excellent position to explore many of the open problems in the SM, and significant progress has been made in addressing the questions outlined above in the past decade. While the Snowmass 2013 neutrino working group report [17] did include a section on BSM opportunities, it was largely focused on resolving the short-baseline anomalies through the addition of an eV-scale light sterile neutrino [18]. Since then, the community has made a significant effort in pushing the boundaries and the potential of neutrino experiments to test for BSM models more broadly, and expanding searches to non-minimal BSM scenarios in the neutrino sector.

8.2.3.1 Heavy Neutral Leptons, Sterile Neutrinos, and the Short-Baseline Anomalies

Heavy Neutral Leptons (HNLs) are right-handed neutrino partners to the standard model active neutrinos. Their existence can provide elegant solutions to present open questions in fundamental physics such as the origin of neutrino masses, the nature of dark matter and the observed matter antimatter asymmetry in the Universe. In the minimal SM extensions, these HNLs, named as such because they are significantly heavier than the standard model active neutrinos, are (quasi) sterile and are produced through mixing with the active neutrinos; as such, they are also commonly referred to as sterile neutrinos, or simply as right-handed neutrinos. However, it is important to bear in mind that, in non-minimal models, they may possess additional interactions (for example, in extensions of the SM with additional gauge symmetries such as B-L, or in non-minimal dark sector models). Depending on their masses, the existence of such heavy neutrinos can lead to multiple phenomenological consequences in a variety of experiments, from neutrino oscillation measurements to colliders (e.g., [19, 20]). In this section we first briefly review the impact of sterile neutrinos on short-baseline neutrino oscillation searches and the reported neutrino anomalies. We will then discuss the phenomenological implications due to HNLs at heavier scales.

The past three decades of experimental neutrino measurements have accumulated hints of observed anomalous short-baseline flavor transformation from multiple sectors of varied neutrino source (proton accelerators, reactors, and intense radioactive sources) and energy (from MeV to GeV scales). These are commonly referred to as the LSND Anomaly, the MiniBooNE Low-Energy Excess, the Reactor Antineutrino Anomaly, and the Gallium Anomaly. Some of these observations have grown in significance over time to nearly or over 5σ, and all share the commonality of having been observed at very short neutrino propagation distances, $L \sim \mathcal{O}(1\,\mathrm{m} - 1\,\mathrm{km})$, relative to neutrino production, i.e., before any three-neutrino oscillation effects are expected to become measurable. These anomalies thus serve as an intensifying experimental impetus for pursuing BSM physics accessible through the neutrino sector. With the generation mechanism of neutrino mass currently unknown, the search for new neutrino mass states and hidden-sector couplings is also theoretically well-motivated.

Over the past ten years, the neutrino community has made significant progress in implementing the primary recommendations of the previous P5 Report by developing a diverse program of small-scale experiments aimed at directly addressing these short-baseline anomalies and at probing the leading (at the time) theoretical explanation for their existence: oscillations from a single eV-scale sterile neutrino state, or a '3+1' scenario.

The community's accomplishments have also extended to confronting the 3+1 oscillation explanation with complementary datasets from MicroBooNE, MINOS/MINOS+, IceCube, T2K, NOvA, Super-K, KATRIN, PROSPECT, and others. Importantly, motivated by the growing tension of experimental data sets under a 3+N light sterile neutrino oscillation hypothesis prompting the consideration of alternate viable anomaly interpretations, the community has additionally developed a rich array of new physics models beyond 3+N sterile neutrino oscillation scenarios. Those models range from exotic flavor transformation ones to dark sector models, many involving HNLs more broadly, and with rich phenomenology accessible at current, planned, and future short-baseline and other experiments. A summary of the anomaly interpretations is provided in Table 8-2, mapping specific models onto broader model classes and onto which anomalies they are meant to address.

While the underlying source of the anomalies remains unresolved, the improvement in knowledge over the past decade is significant, and compels the deeper probes that are possible with current and upcoming experimental capabilities and facilities. Whether the anomalies are caused by a unified, but complex, regime of new physics, BSM effects specific to subsets of neutrino source types, or systematics, the adoption of a multi-probe test strategy is essential to their convincing resolution. Thanks to joint efforts by the theoretical

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactor	Gallium	
Flavor Conversion: Transitions	(3+N) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [21–24]
	(3+N) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[25, 26]
	(3+N) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓	✓	[27–31]
Flavor Conversion: Matter Effects	(3+N) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[32–36]
	(3+N) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[37]
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	✗	✗	[38–40]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	✗	✗	[41]
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[42]
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[43]
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[44–53]
	neutrino dipole up-scattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	✗	✗	[54–61]
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗	[62]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[62]

Table 8-2. *New physics explanations of the short-baseline anomalies categorized by their signature. Notation:* ✓*– the model can naturally explain the anomaly,* ✓*– the model can partially explain the anomaly,* ✗*– the model cannot explain the anomaly.*

and experimental communities, the path forward to the resolution of the anomalies is clearer, as is the possible range of exciting new physics scenarios that can be searched for with current and future facilities.

A key ingredient to unearthing the origins of the short-baseline neutrino anomalies during the next decade is continued support for and full exploitation of short-baseline experiment investments made over the past decade. To that end, measurements by operating or imminent experiments will provide direct experimental tests of most of the anomalies and new information during the first half of the coming P5 period, which will enable tests of many popular interpretations with high sensitivity. This program represents a large international commitment with several of the involved experimental efforts sited at U.S. national laboratories.

Additionally, sustained community effort over the past decade has been expended to develop new experimental concepts, including cutting-edge sources and/or techniques for probing the primary BSM-related anomaly origin categories – flavor transformation phenomena and new particle production – with significantly improved sensitivity over the aforementioned experimental efforts. In some cases, advanced levels of currently achieved technical maturity could enable timely installation and completion of new experimental concepts, potentially providing a new wave of valuable short-baseline information well before the close of the coming P5 period. Other concepts relying on facilities or detectors that may be available later in the coming P5 period can sustain this new wave well into the following decade.

As examples, precise new BSM flavor transformation measurements can be made in the electron disappearance channel using precision measurements of beta decay and electron capture, isotope decay-at-rest sources, or large-volume short-baseline reactor or radioactive source experiments; in the muon disappearance channel using atmospheric neutrinos or neutrinos from decays of accelerator-produced kaons; and using well-characterized flavor content at future long-baseline oscillation facilities or with CEvNS-based measurements of decay-at-rest neutrinos. Furthermore, a vast array of potential dark sector couplings can be probed with high-statistics datasets from intense decay-in-flight, decay-at-rest, and collider beam dump neutrino sources or with atmospheric neutrino fluxes.

Meanwhile, it will be important to continue to investigate complementary and/or indirect probes offered through currently-operating long-baseline accelerator measurements, atmospheric and solar neutrino constraints, precision measurements of weak nuclear decay products, neutrinoless double beta decay measurements, and constraints from cosmology. The recently confirmed Gallium Anomaly, a more than $5\,\sigma$ deficit of electron neutrinos, poses a major riddle worth pursuing.

Full exploitation of the above investments provides plausible paths to convergence of interpretation of the LSND, MiniBooNE, and Reactor Anomalies optimistically as early as the first half of the coming P5 period. Should the interpretations converge, the short-baseline experimental and theoretical landscape will shift, with subsequent priorities depending heavily on what is learned about the various hypothesized anomaly origins. Regardless of what is discovered, we should be prepared to re-evaluate priorities given what will be learned. It is therefore essential that available supporting resources are structured to enable adaptation to developments during the next P5 period and to ensure that timely experimental groundwork is laid for following generations of precision short-baseline measurements.

Besides neutrino oscillation measurements, the existence of HNL can be probed in multiple ways, including: reactor experiments searching for HNL decays in flight, or tests of energy-momentum conservation in nuclear reactions (sensitive to masses between $\sim$ keV and 10 MeV); fixed-target facilities (giving the best sensitivities to HNLs in the tens of MeV to few GeV range in the near future), a broad category that can be further divided into searches from rare kaon decays, beam-dump setups, and searches in accelerator-neutrino-beam environments; and collider experiments (sensitive to HNLs with masses above a few GeV). In the latter case it is worth mentioning the recent development of a series of proposals for transverse (MATHUSLA, CODEX-b, AL3X, ANIBUS and MAPP-LLP) and forward (FASER, SND@LHC, the Forward Physics

Facility [63] and FACET) facilities at the LHC, which provide enhanced sensitivities to HNL in the GeV to tens of GeV mass region. In addition to these terrestrial bounds, a landscape of constraints arises from solar, atmospheric, astrophysical, and cosmological considerations. At present, solar neutrino up-scattering searches provide strong constraints on minimal HNLs, while atmospheric neutrino up-scattering provides novel sensitivity to non-minimal HNLs (such as those interacting with a transition magnetic moment, for example). Likewise, the presence of HNLs in the early universe can be strongly constrained given that they can disrupt the success of big bang nucleosynthesis. A summary of the main phenomenological signals in HNL models is provided in Tab. 8-3.

It is worth stressing that for most of the future options and proposals in the literature, only first estimates on the sensitivity to HNL have been made. Although these demonstrate the potential HNL parameter space coverage, certainly further studies are strongly desirable. Likewise, it would be desirable for future collider facilities to take into account from the start the strong interest and need for searches for long-lived particles in their infrastructure plans, so that detector designs may include searches for HNLs in their baseline physics targets from the start.

As a final remark, it is worth noting the significantly different sensitivities and constraints for non-minimal HNLs scenarios. The phenomenological implications may change significantly once the single-flavor dominance hypothesis is abandoned, or if the HNL possesses new interactions (either with the visible or the dark sector).

8.2.3.2 BSM Signals in the Neutrino Sector: Neutrino Flavor and Neutrino Scattering

Neutrino oscillation experiments are very precise interferometers, sensitive to subleading effects from new physics affecting neutrino flavor transitions. On a separate front, neutrino telescopes – detectors of astrophysical neutrinos – provide a unique avenue to probe BSM effects, given the very long distances traveled by the detected neutrinos (which range from the Earth radius to several gigaparsecs), as well as their ultra-high energies. Finally, astrophysical observations (such as nearby core-collapse supernovae) in the upcoming decade may provide invaluable information and allow us to test neutrino propagation in extremely dense environments. A summary of the main phenomenological scenarios that can lead to observable signatures in neutrino oscillations and neutrino flavor transitions, together with the most relevant experimental signatures for each of them, is provided in Tab. 8-3. For reference, the table also includes a list of some of the planned/proposed experiments where such signals may be investigated (see the provided references for further details).

In the future, a precise measurement of neutrino oscillations in different environments (in matter and vacuum, on different oscillations channels, and/or for experiments relying on different detection mechanisms) will be required to ensure that the three-neutrino paradigm is robust. Because of this, global fits between different data sets may be critical to unveil new physics effects on neutrino flavor, in the same way that they provided the first evidence for a non-zero θ_{13} before it was experimentally measured. The same argument also extends to non-oscillation measurements as well: as a well-known example, CEvNS and oscillation data are strongly complementary in setting bounds on new neutrino interactions, but the full potential can only be unlocked from a joint fit to all available data.

Future advances in this direction will require a joint effort between the experimental and theoretical communities, though. On one hand, global fits rely on experimental collaborations facilitating as much information as possible. IceCube and COHERENT are two notable examples where data release efforts have empowered the theoretical community to derive new bounds on a variety of BSM scenarios, and/or to propose new experimental searches for new BSM signals; however, for many other experiments there is very little information publicly available. On the other hand, the theoretical community often makes use of

theoretical frameworks and parameterizations to derive bounds on new physics (a common example is the use of effective operators at low energies, an approach commonly used in other areas of particle physics as well). However, it is equally important that these frameworks eventually be matched onto viable models, so that the bounds from neutrino experiments can be contrasted with those obtained in other Frontiers of particle physics.

At the same time, while the potential of neutrino facilities for BSM searches is clear, it should be kept in mind that in the past many of these have traditionally been impractical (if not impossible), mainly due to the large systematic uncertainties stemming from our imprecise knowledge of both neutrino fluxes and neutrino interaction cross sections. If we want to fully exploit future experimental capabilities to search for BSM signals, dedicated efforts are required to reduce systematic uncertainties according to the specific needs in each case. The program of supporting measurements in the Neutrino Frontier, including hadron-production measurements for neutrino flux predictions and measurements to improve modeling of neutrino-nucleus interactions, is as important for BSM searches as it is for the standard three-flavor neutrino program. Similar considerations apply to neutrino telescopes: in this case, improving neutrino flavor identification will be key in order to improve experimental capabilities to test for BSM effects, and this will demand a dedicated effort.

Before moving on to the next section let us stress that, while non-standard interactions with charged SM fermions are in some cases straightforwardly tested with traditional ν scattering and oscillation experiments, neutrino self -interactions, νSI, can also be tested by a variety of methods. In particular, cosmological observables (including light element abundances, the Cosmic Microwave Background, and the matter distribution in the Universe) can probe self-interactions at scales of $\sim$eV to $\sim$MeV [64]. Supernovae and other astrophysical neutrino sources can test characteristic self-interaction scales up to $\mathcal{O}(100)$ MeV. Finally, laboratory experiments can access the broadest range of self-interaction scales all the way up to $\mathcal{O}(100)$ GeV.

8.2.3.3 Neutrino Experiments and Signals from BSM Physics in Other Sectors: Dark Matter and Baryon Number Violation

Besides the origin of neutrino masses and mixing, neutrino experiments may also be able to shed some light on two of the other major open problems in the SM: the nature of dark matter, and the origin of the baryon asymmetry of the Universe.

The idea of a dark sector comprising new states that are not charged under the known forces, but are weakly coupled to the standard model via a new mediator, is well motivated from a variety of perspectives. In fact, arguably the dominant empirical motivations for BSM physics searches concern neutrino mass and dark matter: their phenomenology points primarily to weak coupling, but not to a specific new physics scale. Nevertheless, the concept of dark matter direct detection was strongly motivated by the WIMP scenario. In this regard it is worth noting that a wide range of new, well-motivated physics models and dark-sector scenarios have been proposed in the last decade, which would explain the absence of a signal in direct detection experiments, and at the same time may lead to a new physics signals elsewhere.

Modern accelerator-based neutrino beam facilities feature enormous proton beam-target collision luminosities, which can supply copious secondary forward fluxes of dark sector particles. Thus, neutrino beam experiments allow for BSM physics searches in a way that is complementary to Energy Frontier experiments. At the same time, well-motivated physics models for non-minimal dark sectors predict cosmogenic signals complementary to those in conventional direct DM detection experiments. These often have less intense and more energetic fluxes, to which underground, kiloton-scale neutrino detectors can be readily sensitive. Consequently, both the theoretical and experimental neutrino communities are now heavily exploring the potential of neutrino facilities to test for signals from non-minimal dark sectors. The landscape of potential

signals at neutrino experiments coming from BSM physics in other sectors is wide, as summarized in Table 8-3.

On a separate front, neutrino experiments have been (and will be) widely used to search for Baryon Number Violation (BNV). Although there is no direct evidence of proton decay so far, the observed matter-antimatter asymmetry suggests that baryon number must be violated at some level. While the main focus of BNV experiments is on proton decay searches, other equally important baryon and/or lepton number violating processes include dinucleon decays and neutron-antineutron oscillations, which must be studied as well. Regarding experimental detection prospects, detector mass is obviously a clear and crucial characteristic in next-generation BNV searches, and clearly Hyper-Kamiokande has the advantage in that respect. However, detector technology will also play an important role. In fact, DUNE's excellent imaging capabilities and JUNO's superb resolution offer advantages in some channels over Hyper-Kamiokande's larger mass. The proposed Theia [65] experiment would combine the advantages of the large mass of a water Cherenkov detector with the good resolution of a liquid scintillator detector. With this worldwide program, should a BNV signal be observed by any one detector in the next generation, confirmation from other detectors using different technologies would provide powerful evidence of new physics [66].

In order to make significant progress in any of the directions outlined above in the next decade, BSM searches should be considered a high priority in the experimental design decisions for the future. A closer collaboration with the nuclear physics community would also be needed, as well as steps to enhance simulation tools for BSM processes and related backgrounds. Finally, new physics searches at neutrino facilities would significantly benefit from a closer collaboration across particle physics frontiers, given the strong complementarity with respect to similar efforts in other areas. It would also be desirable that experimental sensitivities and constraints be presented in a model-independent way as much as possible, to ease reinterpretation and recasting of the obtained results to other frameworks or BSM scenarios.

BSM Scenario	Sources	Signatures	Example Experiments
HNL [67]	Colliders	HNL decay	ATLAS, CMS, FASER, Belle II, ...
	Nuclear decays	Nuclear decay kinematics	KATRIN/TRISTAN, HUNTER ...
	Fixed target	HNL decay	DUNE ND, SHiP, ICARUS, ...
	Atm. & solar νs	Distorted recoil spectrum	DUNE, HK, IceCube/DeepCore, ...
		HNL decay, double bangs	
	Early Universe	Cosmological parameters ($N_{\rm eff}$)	Simons Observatory, CMB-S4, ...
Non-unitarity [68]	Beam & Atm. νs	Deviations from 3-ν mixing (ND & FD)	DUNE, ESSνSB, HK, ...
LED [68]	Reactor νs	Distortion of oscillated spectra (FD & ND)	JUNO, TAO,...
	Beam νs		DUNE, ...
	Atm. νs	Anomalous matter effects	Icecube, KM3NeT, ...
NSI & light mediators [68, 69]	Reactor & Stopped-π sources	Distortion of CEvNS rate	COHERENT, CONNIE, CONUS, ...
	Solar, Beam, Atm & SN νs	Anomalous matter effects	DARWIN, DUNE, T2HKK, HK, IceCube, ...
	Beam νs	Anomalous appearance, $\nu - e^-$ scattering, tridents	DUNE ND, T2HK ND, IsoDAR, ...
	Collider νs	Distortion of CC spectrum	FASERν, ...
Long-range forces [68]	Solar & Atm ν	Anomalous matter potential	HK, JUNO, DUNE, ...
	UHE Astrophysical nus	Distorted flavor ratios	HE Neutrino Telescopes
ν-DM interact. [68]	Reactor & solar νs	Distorted oscillated spectra, or time-dependent oscillation params.	JUNO, ...
	Beam ν		DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
ν self interact. [64, 70]	SN νs	SN extra energy loss, distortion in neutrino spectra	DUNE, HK, JUNO, ...
	UHE Astrophysical νs	Distorted spectra	HE & UHE ν telescopes
	Early Universe	Effects on CMB, BBN, & structure formation	CORE, PICO, CMB-S4
	Beam & Collider νs	Missing energy & p_T in ν scattering	DUNE ND, Forward Physics Facility, ...
ν decay [68]	Reactor νs	Distortion of oscillated spectra	JUNO, ...
	Beam νs		DUNE, MOMENT, ESSνSB, HK, IsoDAR, ...
	Atm. νs		INO-ICAL, KM3NeT-ORCA, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
CPT violation [68]	Beam νs	Different ν and $\overline{\nu}$ osc. params.	DUNE, ESSνSB, HK, ...
	Atm. νs		IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra	HE & UHE Neutrino Telescopes
Lorentz violation [68]	Beam νs	Sidereal modulation of event rate	DUNE, ESSνSB, HK, ...
	Atm. νs		IceCube, DUNE, ...
	UHE Astrophysical νs	Distorted flavor ratios & spectra, velocity dispersion	HE & UHE Neutrino Telescopes
Quantum decoh. [68]	Beam νs	Distortion of oscillated spectra	DUNE, IsoDAR, ...
	Atm. νs		KM3NeT, IceCube, HK, ...
	UHE Astrophysical νs	Distorted flavor ratios	HE Neutrino Telescopes
B violation [66]	Detector mass	Nucleon decay, $n - \overline{n}$ oscillations	DUNE, HK, JUNO, ...
Dark Matter [71, 72]	DM annihilation, DM decay	Excess of νs from Sun or Earth	HK, DUNE, IceCube ...
	Boosted DM, slow-moving DM	Scattering, or up-scattering & decay	
	Fixed target	Decay	DUNE, T2HK, SBN, FASERν, ...
		Scattering, or up-scattering & decay	PIP2-BD, SBN-BD ...
Milli-charged particles [71]	Fixed target	Scattering	DUNE ND, T2HK ND, IsoDAR, ...
	Atmosphere		DUNE, HK, JUNO, ...

Table 8-3. *Summary of the most significant experimental signatures for the BSM scenarios covered in this document. Example experiments sensitive to each scenario are also provided (see references for the full list). Abbreviations: Atm.=Atmospheric, B=Baryon number, CC=Charged Current, CEvNS=Coherent Elastic ν-Nucleus Scattering, DM=Dark Matter, FD=Far Detector, HE=High Energy, LED=Large Extra Dimensions, ND=Near Detector, NSI=Non-Standard Interactions, SN=Supernovae, UHE=Ultra-High Energy.*

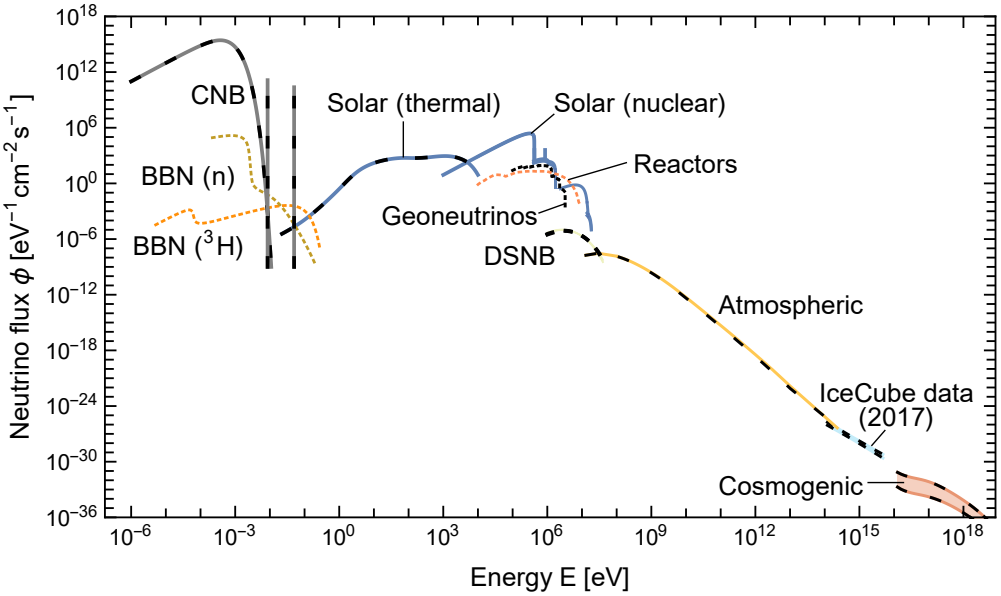

Figure 8-5. *"Grand Unified Neutrino Spectrum" of natural neutrinos arriving at Earth (reactor neutrinos also shown). Figure from Ref. [73].*

8.2.4 Neutrinos as Terrestrial and Astrophysical Messengers

Neutrinos are produced copiously by natural sources over many orders of magnitude of energy. The natural neutrino spectrum is summarized in Fig. 8-5. By virtue of their weak interactions, neutrinos can emerge from deep inside otherwise inaccessible sources. They serve as astrophysical messengers, providing unique information about the nature of the sources themselves; in conjunction with other types of emissions (photons, gravitational waves, charged particles) neutrinos provide a deeper and richer scientific story. Furthermore, astrophysical source emission, when sufficiently well understood, enables studies of the properties of neutrinos themselves– the discovery of neutrino oscillations in atmospheric and solar fluxes by Super-Kamiokande and the Sudbury Neutrino Observatory was a spectacular precedent for this. Cosmological studies also provide important contributions to our understanding of neutrino properties, with sensitivity to the number of neutrinos, the sum of their masses, and potential new neutrino interactions.

Detection techniques and types of information gained are highly dependent on the neutrino energy regime. Current-generation detectors have measured neutrinos from a few hundred keV up to the PeV regime. Expanding outside of this energy interval is unexplored territory, requiring novel technology.

In the regime from a few to a few tens of MeV, future precision measurements of solar neutrinos offer the potential to resolve uncertainties in the metallicity of our Sun, to inform our understanding of stellar evolution, to probe the interaction of neutrinos with matter in a unique environment, to search for non-standard interactions and new physics effects, and to perform precision tests of the three-flavor neutrino mixing paradigm. Building on the ground-breaking discoveries and technological developments of the Borexino experiment, a suite of next-generation detectors is under development, which leverage novel technology to improve background discrimination in order to enhance sensitivity to these low-energy neutrinos. SNO+ is now the largest, deepest operating liquid scintillator detector, and JUNO will come online in a few years, with a large volume and excellent sensitivity to oscillation parameters and higher-energy solar neutrino studies. A future program can leverage multi-purpose detectors that can also target

dark matter or other low energy physics; these detectors include noble liquid detectors, or hybrid neutrino detectors, such as Theia, which seek to combine both Cherenkov and scintillation signatures for additional particle and event identification capabilities.

A similar suite of detectors is also sensitive to antineutrinos produced within the earth – so-called geoneutrinos. Observations to date have been made at the KamLAND and Borexino experiments, but additional measurements are needed in order to fully interpret the results and implications in light of different models for heat production within the Earth. Of particular interest are measurements of the U/Th ratio; a measurement of the flux produced from the mantle, which can be inferred using a suite of results from different geographical locations, or measured directly with an ocean-bottom detector; and the potential to detect the potassium antineutrino flux.

Moving up in energy, the next galactic core-collapse supernova is expected to be detected in photons, neutrinos, and gravitational waves and will carry a formidable amount of information on the physics of the collapse of massive stars. This multi-messenger detection will be crucial to test our conjectures on the supernova mechanism. To this end, progress is being made in order to use neutrinos to alert astronomers and gravitational wave physicists of the core collapse as soon as possible through the SNEWS [74] network. Neutrinos will carry clear signatures of the nature of astrophysical event, such as sharp neutrino flux cutoff that would indicate the formation of a black hole. Despite swift progress in the field in the last decade, the impact of neutrino flavor mixing in the dense supernova core remains to be assessed and it is one of the main goals for the next decade, due to its implications on the supernova hydrodynamics, nucleosynthesis and detectable neutrino signal. In order to maximize the physics we will extract from this once-in-a-generation event, it is imperative to have neutrino experiments with high uptime and using a variety of detection technologies in order to enhance the statistics of the measurement, but also to ensure measurements of all neutrino flavors. It is expected that the next supernova burst will test the existence of new physics or place stringent constraints on it; however, for this purpose, a consistent modeling of new physics in the source is mandatory. The diffuse supernova neutrino background (DSNB)– the relic neutrinos from core-collapse supernova which have occurred since the beginning of the Universe– is another interesting target, for which first detection may be achieved in the near future by gadolinium-doped water Cherenkov experiments such as Super-Kamiokande-Gd. The detection of the DSNB will push low-energy neutrino astronomy to extra-galactic scales and will provide complementary insight to the detection of supernova burst neutrinos on the supernova population as well as on new or exotic physics.

Moving to the GeV regime, atmospheric neutrino observation by next-generation detectors planned to operate in near future will continue to bring insights. Information on neutrino oscillation parameters, especially θ_{23} octant, mass ordering, and δ_{CP}, will enhance the knowledge from terrestrial long-baseline experiments. Atmospheric neutrinos also have sensitivity to a range of BSM physics, including sterile neutrinos, Lorentz invariance violation, non-standard interactions, and CPT violation. Precise measurement of the atmospheric neutrino flux is also an important topic, not only for neutrino oscillation analysis, but for other physics like baryon number violation searches, because the atmospheric neutrino signal is the primary background for these searches. For that purpose, it is necessary to reduce the uncertainty of hadron production by primary proton interactions. In addition, searches for prompt neutrinos from atmospheric charm production by cosmic rays in neutrino telescopes is an interesting topic.

At the highest energies, the advent of real-time astronomy in IceCube has already led to identification of a handful of likely cosmic sources of ultra-high-energy neutrinos. The expected growing numbers of such detections as well as the larger statistics enabled by upcoming neutrino telescopes such as IceCube-Gen2 and KM3NeT will bring new understanding of particle acceleration in the sources as well as the mechanisms powering cosmic accelerators. In the next decade, we expect the emergence of radio-detection-based neutrino telescopes that will be sensitive up to the ZeV range in energy. This will bring information on cosmic

accelerators at the most extreme energies, as well as information on neutrino properties and new searches for BSM physics.

On the very low-energy end of the spectrum, the indirect effects of cosmic background neutrinos have been well studied using multiple types of cosmological survey data, and these data have brought key understanding of the neutrino absolute mass scale, as well as the number of neutrino degrees of freedom. A long-standing, very challenging goal is to *directly* measure the cosmic neutrino background detection. In this endeavor, PTOLEMY is the only long-term project with the aim of direct cosmic neutrino background. Cosmological data and laboratory-based data are highly complementary in this area.

8.2.5 Neutrino Properties

The existence of non-zero neutrino mass is, to date, the only laboratory-based observation of BSM physics. The disparity of mass scales between neutrinos and other fundamental particles suggests a high-energy scale for neutrino-mass generation. In models where this mechanism lies at or below the TeV scale, the physics of neutrino mass may be accompanied by complementary signatures at colliders. In models where the scale is higher, experiments probing the nature of neutrino mass are the only feasible way of exploring this new physics. The observation of neutrinoless double beta decay would provide direct evidence that lepton number is violated, opening a path to baryogenesis via leptogenesis in the early universe. As such, direct tests of the scale or nature of neutrino mass target some of the most central open questions in fundamental physics today.

The absolute mass scale of the neutrino is accessible through several complementary measurements, though notably not through neutrino oscillations. Laboratory probes measure the kinematics of beta decay, a field that has recently seen substantial technical and scientific advances. These measurements are complementary to astrophysical and cosmological approaches. Searches for neutrinoless double beta decay investigate the Majorana or Dirac nature of the neutrino. The next generation of these experiments at the ton-scale is prepared to begin construction early in the coming P5 period. Completion of these experiments is a continuing focus of the neutrino physics community. Pursuing the physics associated with neutrino mass was a key Science Driver in the 2014 P5 report, and the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment was a top priority item in the 2015 Nuclear-Physics Long-Range Plan, a commitment that continues today under the stewardship of the Department of Energy Office of Nuclear Physics. A rich research and development program toward beyond-ton-scale sensitivities is underway. The envisioned experiments would be sensitive to a wide range of neutrino-physics phenomena, and the technologies under development may have broad applications in particle physics and beyond.

Other neutrino properties may be connected to extensions of the standard model, yet are not observable via oscillations. Neutrino electromagnetic properties are of fundamental interest, and the nascent program measuring coherent elastic neutrino-nucleus scattering (CEvNS) offers intriguing sensitivity [69]. Lorentz and quantum mechanical properties of neutrinos may also illuminate new physics that is inaccessible through other techniques.

8.2.5.1 Neutrino-Mass Scale

What is the absolute mass scale of the neutrino? Complementary experimental approaches currently set limits on this mass scale; when a non-zero mass is measured, will it appear in other probes in a way consistent with our current understanding?

Direct, kinematic measurements of the neutrino-mass scale are essential to disentangle this property from the model dependence of cosmological concordances, supernova dynamics, or neutrinoless double-beta decay. The improving sensitivity of all neutrino-mass-measurement techniques raises the possibility of a fruitful disagreement between methods. A measured neutrino mass m_β within the projected KATRIN sensitivity [75] would constrain the available model space for neutrinoless double-beta decay, and require the introduction of new physics to be reconciled with current cosmological data [76]. Any positive measurement should be followed up using a different experimental technique and/or a different decaying isotope. There is a strong consensus to pursue realization both of cyclotron-radiation emission spectroscopy for a next-generation tritium experiment such as Project 8 [77], and of microcalorimetry with embedded ^{163}Ho as developed by ECHo and HOLMES [78], to ensure this flexibility. Continued effort to identify additional isotopes for kinematic m_β measurements could open up new experimental possibilities.

8.2.5.2 The Nature of Neutrino Mass

What is the mechanism that generates neutrino mass? Is the neutrino a Majorana fermion or a Dirac fermion? How can the sensitivity of neutrinoless double-beta decay searches best be improved beyond the inverted-ordering region targeted by the next generation of experiments?

Detection of neutrinoless double beta decay is the only known method with plausible sensitivity to the Majorana nature of the neutrino, one of the most important open questions in particle physics. Techniques aimed at its discovery have been developed in several isotopes with tens-to-hundreds kg scale demonstrators paving the way for ton-scale and larger discovery-class experiments over the last Snowmass period. The proposed experiments use a range of detection techniques: loaded liquid scintillator, gas and liquid time projection chamber, bolometer, and solid-state detectors are all competitive approaches. Certain experimental challenges, notably isotope procurement and background measurement and control, are broadly shared among experimental schemes. The coming ton-scale generation of experiments will probe effective Majorana neutrino masses, $m_{\beta\beta}$, as small as 10 meV in discovery mode, fully exploring the parameter space favored by the inverted mass ordering and covering a large fraction of the parameter space associated with normal neutrino mass ordering under the light neutrino exchange mechanism.

A portfolio of international experiments, representing multiple isotopes and detection technologies, will both probe this parameter space and, importantly, permit confirmation of any discovery. There is strong consensus for the goal of building at least two ton-scale experiments with U.S. leadership, multi-agency, and international support, as well as continuing participation in other programs worldwide.

The neutrino community is pursuing a thriving R&D program for beyond-ton-scale neutrinoless double-beta decay searches (e.g. [79, 80]). This program offers exciting opportunities for upgrades that would improve the sensitivity of ton-scale experiments, and for future sensitive, ultra-low-background detectors that can access a broad physics program. Support for R&D in multiple isotopes and with multiple technologies is recognized as vital to ensure readiness to fully explore the range of half-lives associated with normal neutrino mass ordering, or to confirm and pursue precision measurements in the case that neutrinoless double-beta decay is discovered at the ton scale. Theoretical progress in computation of nuclear matrix elements is also critical in this endeavor [81].

8.2.5.3 Neutrino Electromagnetic Properties

Are the electromagnetic properties of the neutrino consistent with standard-model predictions arising from radiative effects?

In the standard model, neutrinos have small charge radii induced by radiative corrections. The predicted values of the electron and muon neutrino charge radii are less than an order of magnitude smaller than the current experimental upper limits and can be tested in the next generation of accelerator and reactor experiments through the observation of neutrino-electron elastic scattering and CEvNS. Precision measurements of the neutrino charge radii would either be an important confirmation of the standard model, or would discover new physics. The same types of experimental measurements are also sensitive to more exotic neutrino electromagnetic properties: magnetic moments and millicharges, which would be certainly due to new BSM physics. The discovery of millicharges or anomalously large neutrino magnetic moments would have also important implications for astrophysics and cosmology.

8.2.5.4 Other Neutrino Properties

Can probes of other neutrino properties, such as the neutrino lifetime or Lorentz-invariance violation in the neutrino sector, shed light on physics beyond the standard model?

Since neutrinos are very elusive, they can have very exotic properties that have not been discovered so far, e.g., properties that violate the Lorentz and CPT symmetries and gravitational interactions that violate the equivalence principle. Data from a wide range of neutrino experiments have already been used to constrain many of these exotic properties. There is no specific experimental plan aimed at investigating these properties, but experimentalists and phenomenologists should be alert to opportunities to use new experimental data for the exploration of all non-standard neutrino properties.

8.2.6 Neutrino Interactions

A thorough understanding of neutrino cross sections in a wide range of energies is crucial for the successful execution of the entire neutrino physics program. Support is needed for all stages of achieving this understanding, including new experimental measurements (e.g. [82]), improvements to theoretical neutrino scattering models [83], and refinements to interaction simulations.

Neutrino interactions constitute either signal or background for a variety of exciting physics measurements planned in the near and far future. The scientific reach of these efforts will ultimately depend on obtaining a detailed knowledge of the interaction physics. The complex nuclear targets used by most experiments present a particular challenge for obtaining the needed theoretical precision. A far-reaching program of new measurements is needed to inform theoretical improvements. The success of the field will also depend on support for this foundational theoretical work and its implementation in *event generators*, the computer programs used to simulate neutrino scattering for experimental analyses [84].

There are valuable proposed cross-section measurements applicable to future programs, including new electron scattering measurements, new pion scattering measurements, measurements at long- and short-baseline experiments, and dedicated neutrino scattering measurements. These measurements provide new information to develop interaction model theory and improve its implementation in event generators. This is another area of overlap with the nuclear physics community.

The community faces important challenges:

- The exact role of and impact of the suite of new cross section measurements on oscillation physics is not yet completely elucidated. A dedicated exercise, overseen by oscillation experimental programs

but also involving theory and external measurements, is needed to assess the benefits of those measurements, and to refine what specific measurements could be valuable.

- Event generators are a key tool for neutrino experiments, as elsewhere in HEP [84]. There are several available generators, each using different approaches, and all valuable to the community. However, improvements to these generators can take significant time to implement, and it is challenging to keep them up to date with state-of-the-art modelling. This is in part due to the necessary work being undervalued relative to other activities. The situation needs to be improved, and incentives aligned with the needs of the experimental program should be provided. We also advocate for continued grassroots efforts to identify and resolve short-term issues and to identify how generators should interface most constructively with experiments.

- There will be a wealth of important experimental cross-section data in the short term, but the needs of the oscillation program may change. We endorse efforts by experimental collaborations to have data preservation plans which allow for re-analysis of the unique capabilities of experiments.

8.2.6.1 Low-Energy Cross Sections

Low-energy neutrino scattering on nuclei will be a signal or background process in a variety of exciting physics measurements in the near and far future. The recent observations of CEvNS have spurred renewed interest in the process as a probe of fundamental properties of the neutrino, weak interactions, and nuclear properties. First-light measurements have already produced significant new constraints in these areas and the impact of future precision measurements of the total cross sections and recoil distributions is still being explored theoretically. This process will also be an irreducible background for direct dark-matter searches and a controllable background for accelerator-produced dark-matter searches at stopped-pion facilities where preservation of the timing structure of the neutrino flavors reduces the CEvNS background relative to the dark-matter signal.

Low-energy inelastic scattering processes provide the foundational detection mechanism for solar, reactor, stopped-pion-based oscillation experiments and supernovae. In many cases, the cross sections for these interactions have never been measured, and the simulation capabilities needed to interpret future measurements are very limited. In some cases, there are nuclear physics topics interesting in their own right that can be explored in dedicated neutrino experiments.

- Future planned CEvNS (COHERENT [85], CCM [86]) measurements will make significant improvements in precision that expand our understanding of neutrino properties and extend the sensitivity of BSM tests and hidden-sector searches; electron-scattering experiments play a vital role in isolating modifications to the cross sections from the finite size of the nucleus.

- Measurements of inelastic cross sections on nuclei relevant for oscillation and supernova physics are critical to the success of these programs. While facilities and detection technologies exist to make these measurements, focused and dedicated efforts will be required to achieve the needed precision.

8.2.6.2 Medium-Energy Cross Sections

Accelerator-based short- and long-baseline neutrino oscillation experiments operate in the medium energy regime of ∼0.1–20 GeV. A precise extraction of oscillation parameters by these experiments requires relevant neutrino cross sections to be well modeled. Future programs recognize this and have designed highly capable

suites of near detectors with new capabilities to make needed cross-section measurements. The DUNE collaboration plans to use precision detectors to make measurements at multiple off-axis angles.

Various processes, including quasi-elastic scattering, multi-nucleon knockout, resonance production, and both shallow- and deep-inelastic scattering play important roles at medium neutrino energies [87–89]. The neutrinos generated by accelerators and atmospheric sources have a broad energy spectrum. Multiple channels contribute to the observed event rates, and, because neutrino oscillations are energy-dependent, the cross section for each process as a function of energy needs to be well understood (with well-quantified uncertainties) to interpret measurements correctly. Rare charged- or neutral-current processes may also be important as signal or background as well, especially in searches for exotic physics. Nuclear dynamics of the neutrino target material (commonly carbon, oxygen or argon) greatly complicate the needed theoretical calculations. Furthermore, neutrino experiments also need predictions for all relevant flavors of neutrinos (ν_e, ν_μ, ν_τ) and antineutrinos. Reliable energy-dependent total cross-section predictions are essential but insufficient on their own: accurate estimation of the efficiency and purity of an experimental selection may depend on various details of the composition and kinematics of exclusive final states. Accounting for missing energy (due to, e.g., undetected neutrons) when performing neutrino calorimetry is also a critical task that requires full exclusive final-state modeling. The unprecedented increases to beam exposure and detector size also enable explorations of final states in increasing detail.

Various efforts are currently underway or proposed which will provide useful results for better understanding neutrino interactions. These include indirect but highly valuable new measurements with electrons [90] (E12-14-012, e4ν, LDMX, A1, eALBA) and pions (LArIAT, WCTE, ProtoDUNE) as well as direct neutrino cross-section measurements by long-baseline experiments (T2K, NOvA, DUNE, Hyper-K), short-baseline experiments (MicroBooNE, SBND, ICARUS) and dedicated neutrino scattering experiments (ANNIE, MINERvA, NINJA, H/D bubble chambers, FASERnu, SND@LHC, nuSTORM).

8.2.6.3 High-Energy Cross Sections

Understanding neutrino interactions at energies from the few hundreds of GeV to the TeV scale and beyond is important for studying ultra-high-energy astrophysical neutrinos. In this energy regime, deep inelastic scattering of neutrinos off individual quarks inside nucleons is the dominant interaction mode. Cross-section calculations with small uncertainties are available up to 100 PeV. At still higher energies, theoretical predictions currently have relatively large QCD-related uncertainties. Laboratory measurements of neutrino scattering at very high energies are difficult; no neutrino cross-section data are yet available for energies above about 350 GeV, although information is available from atmospheric neutrinos [91–93]. FASERnu, SND@LHC, and experiments at the Forward Physics Facility (FPF) will extend experimental reach into the TeV scale.

8.3 Enabling Tools and Technology

In this section we describe the tools and technology that enable the success of Neutrino Frontier physics, including computing and software, accelerators, and detector instrumentation. In many cases, relevant issues and opportunities are shared with other physics Frontiers; in other cases, problems in neutrino physics require specialized tools to solve them.

8.3.1 Computing and Algorithms

8.3.1.1 The Changing Computing Landscape

Computing is a critical enabling technology for neutrino experiments, as it is across all of High Energy Physics, for both small [94] and large [95] experiments. A central challenge facing all of us is that computing is undergoing a phase change: our history of using "embarrassingly parallel" resources like the Open Science Grid will not be able to continue to increase in scale to meet our needs. This change reflects an underlying dynamic beyond the control of the HEP community: the speed of individual computing cores is no longer increasing as it once did, the so-called "end of Moore's law," and thus the international funding agencies are no longer prioritizing investment in these types of computing resources. The good news is that there are ways past this barrier which make use of more specialized "accelerator" hardware like GPUs and FPGAs, and national and international funding agencies have been investing in computing based on these technologies. Therefore, in principle, enough "computing cycles" are expected to be available in the future to enable neutrino science. However, these "High Performance Computing" (HPC) facilities typically take the form of a smaller number of specialized facilities ("leadership class" computers or "supercomputers"). We should anticipate a more complicated computing landscape, with different facilities optimized for different types of work. It is plausible that simulation, plot making, statistical analysis, and machine learning will all happen on different computing resources optimized for each type of problem. This challenge is not limited just to large experiments like DUNE with significant computing organizations, but will affect all experiments at all scales, so funding opportunities for computing development should be inclusive. Given the fast-paced change in these technologies, and the shared nature of the challenge across all areas of HEP, we strongly support the Computing Frontier recommendation to create a HEPAP subpanel on computing to advise and coordinate across the field at a higher frequency than Snowmass planning exercises.

Adapting successfully to the move to specialized computing architectures will require significant new software development since we are only in the earliest days of making use of these facilities in many neutrino experiments, as highlighted by Critical Challenge 3 in the Computing Frontier report. Achieving this adaptatioon will require support for the development of both shared software solutions (Critical Challenge 2) where they are possible as well as in experiment-specific contexts. DUNE provides examples of both: it is already making use of some LHC-developed tools for data movement and workflow management, which shows the possibility for sharing solutions. However, DUNE will also have specialized needs which differ from colliders. For example, DUNE will have a relatively small number of events compared to an LHC experiment, but each normal event will be gigabytes in size, making processing a challenge in normal circumstances. In addition, DUNE also anticipates recording supernova burst candidates approximately once per month, and each of these candidates will produce terabytes of data over the course of 100 seconds which then needs to be processed quickly to provide potential early warning to the other observatories. Preparing for these and the many other experiment-specific computing challenges will require training a new generation of physicists how to make effective use of these new computing architectures and providing a career path for them so their expertise is not lost, which is highlighted in Critical Challenge 4. The move to these computing paradigms also presents some organizational challenges: we need an access model which allows trust to flow from the experiments on to the owners of computing (as we currently have with the OSG), and experiments will need to adapt to proposal-driven, rather than fair-share, distribution of computing resources, which requires additional planning.

8.3.1.2 Common Software Tools

Neutrino experiments' computing needs extend beyond hardware into common software challenges. These shared tools can be broadly divided into simulation packages and software frameworks. These tools are faced with two Critical Challenges as outlined in the Computing Frontier report: both the general need for continuous development of existing tools (Critical Challenge 1) and the challenge of supporting work for cross-cutting software (Critical Challenge 2).

All areas of neutrino physics, from early design and R&D to mature experiments focused on data analysis rely critically on a suite of simulation tools shared across the community [96]. GEANT4 is the de-facto standard in detector simulation, and in many experiments is a large, if not dominant, share of the total computing burden. A critical part of the challenge of moving to modern, heterogeneous computing is development work in GEANT to support these new environments. Microphysical simulation tools in neutrino physics (e.g., neutrino interaction generators, liquid noble element simulations) present a different challenge. These tools generally are not costly computationally. Instead, because of their wide variety, they present challenges of coordination and the need to develop common interfaces so they can be put into broad use. All of these tools further depend on physics development to take advantage of new theoretical work and new measurements such as test-beam experiments measuring hadron-Ar cross sections or short-baseline experiments measuring neutrino scattering cross sections. The development of neutrino interaction generators is particularly vital since it is a key part of achieving the unprecedented 1% systematic-uncertainty targets of the DUNE experiment.

Modern neutrino experiments are increasingly relying on a variety of shared software frameworks. Some of these frameworks have been developed and are supported by the national labs and serve only HEP experiments, or in some cases only neutrino experiments. Examples include ART, LArSoft, and Wire-Cell. Given the central role these frameworks play in recording and using experiment data, continued support throughout and even past the lifetime of the experiments using them is critical to enable continued use of the data to make physics measurements. Additionally, neutrino experiments are making increasing use of "public" frameworks, especially in the area of machine learning, such as TensorFlow and PyTorch. Already, using these frameworks creates a support challenge where the frameworks integrate into experiment software stacks, since these external products typically update much faster than experiment software does. These challenges will only increase as the use of these frameworks increases, and particularly if we find we are contributing modifications back into the frameworks to better support our data formats and workflows.

8.3.1.3 Data Preservation

Achieving DUNE's 1% systematic uncertainty target requires more than just generator development, however. Data have been taken and will soon be taken at a range of scattering experiments. However, the critical time for the use of these data will be well after the end of those experiments, e.g., during the later stages of the DUNE experiment when systematic uncertainties become increasingly important. It is clear from the experience of trying to use older data today (e.g., hydrogen and deuterium bubble chamber data) that we need to preserve these data and their analysis context with much greater fidelity, so that they can be continuously re-interpreted through newly developed theoretical models. The MINERvA experiment is working actively on this project now, but their effort, and those of current and near future experiments, would benefit substantially from cross-community tools and best practices. The experience of the nuclear physics community also suggests that continuous institutional support will be required to ensure the utility of and access to data after the end of the current experimental effort [97]. This need is highlighted in Critical Challenge 1 of the Computing Frontier report.

8.3.1.4 Machine Learning

Neutrino experiments were early movers in the use of modern machine learning (ML) techniques since computer vision techniques like convolutional neural networks were readily adaptable to the relatively large, homogenous detectors commonly used to detect neutrinos. The use of machine learning has rapidly expanded to a wide range of different techniques applied to different types of problems, as has occurred across the HEP community [98]. A key feature of modern deep learning, which differs from past ML efforts in HEP, is that it relies heavily on externally developed frameworks. This change presents an opportunity, since these frameworks are supported by large communities and often have good support for modern accelerated computing hardware (Critical Challenge 3), but it creates a new need to develop interfaces between these ML frameworks and the tools more commonly used in HEP [99]. There is also strong motivation to integrate ML/AI capabilities closer to the data source at the detector. This development work has the potential to support experiments at all scales if it is pursued as a cross-cutting effort rather than individually within experiments (Critical Challenge 2).

8.3.2 Artificial Neutrino Sources

The primary artificial neutrino sources of wide use in the Neutrino Frontier are accelerator-produced beams. Reactors have been and are planned to be used for multiple experiments, and future ideas for novel sources exist as well.

8.3.2.1 Horn-Focused Neutrino Beams

Conventional decay-in-flight neutrino beams use high-energy protons striking a target to generate short-lived hadrons (mainly $\pi^{\pm}$ and $K^{\pm}$) that are focused using magnetic horns before decaying into neutrinos. Selecting positively charged hadrons results in a beam that is primarily ν_{μ}, while selecting negatively charged hadrons results in a beam that is primarily $\overline{\nu}_{\mu}$. Current long-baseline experiments require hundreds of kW proton beam power to produce sufficient neutrino flux at their detectors.

The current landscape for neutrino beams that result from focused hadrons includes the long- and short-baseline program at Fermilab and the J-PARC neutrino beam to T2K. Both of these laboratories will be a major international focus for long-baseline experiments over the next decade with the upgrade of the J-PARC beamline for Hyper-Kamiokande in Japan and the construction of the initial phase of the LBNF neutrino beamline for DUNE at Fermilab. J-PARC and LBNF Phase I have planned proton beam powers of 1.3 and 1.2 MW, respectively. A beam power upgrade of the LBNF beamline from 1.2 to 2.4 MW in the second phase of DUNE will be crucial to maximizing its physics reach in a timely manner. Fig. 8-6 shows the beam power and energy for current and future long-baseline beams.

The Fermilab beam upgrade will be accomplished in two phases. The PIP-II project will replace the current 400 MeV linac at Fermilab with a new 800 MeV H^- accelerator capable of delivering the 1.2 MW power for Phase I of DUNE. However, after this upgrade the amount of beam that can be transmitted to the Main Injector will be limited by the capacity of the 8 GeV Booster synchrotron. To reach the higher power needs of DUNE Phase II, the Booster will need to be replaced or upgraded. The Booster replacement could be based on a continuation of the 800 MeV linac up to 2-3 GeV [4], which can then be followed by either a new rapid cycling synchrotron or by continuing the linac to all the way up 8 GeV [100]. Modifications to the LBNF beamline will be required to handle the higher beam power in Phase II [101]. Some components such as the shielding, absorber, and decay pipe, are being designed for a 2.4 MW beam. However other

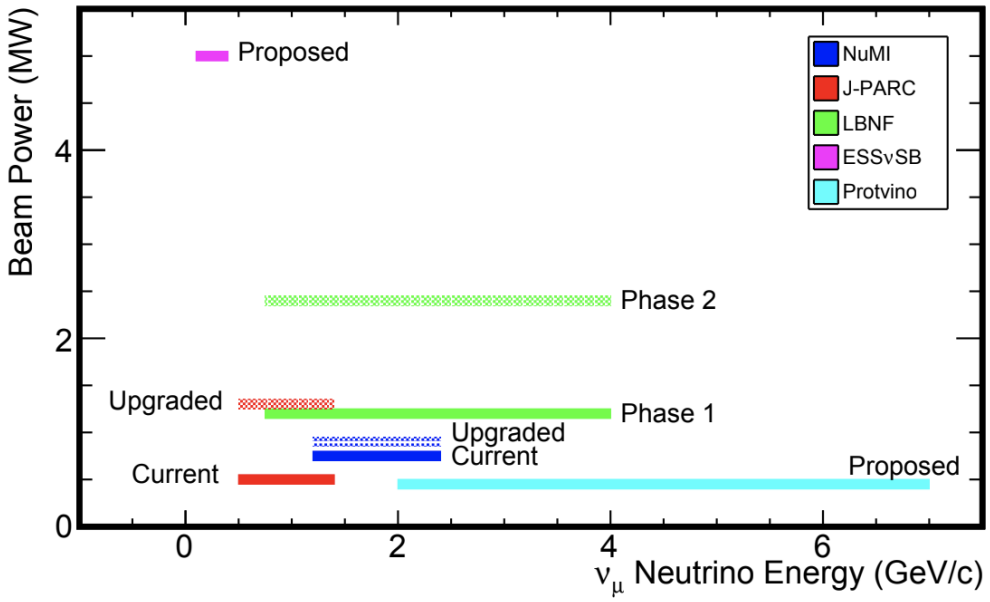

Figure 8-6. *Neutrino beam power vs. energy for current and future long-baseline neutrino beams. The energy range shown here is the approximate width to half-max around the beam peak energy.*

components, such as the target and first horn, will need to be redesigned for Phase II. Significant R&D on target materials will be essential to ensure target reliability in Phase II and allow for accurate prediction of the component lifetimes [102]. Additional information as well as details on physics opportunities with Fermilab beam upgrade paths are discussed in [4, 5, 13, 103–105].

A design study has recently been produced on the feasibility of creating an intense neutrino super beam with a beam power of up to 5 MW using 2.5 GeV protons at the European Spallation Source [106]. There is also a proposal to send a neutrino beam from Protvino to KM3NeT/ARCA [107].

Near detectors and other beamline instrumentation are required to constrain flux uncertainties, which result from uncertainties in hadron production and uncertainties in the parameters of the beamline, such as horn current and position. Measurements of the production of hadrons in the interactions from dedicated hadron production experiments also improve our knowledge of the neutrino fluxes in accelerator-generated beams. The NA61/SHINE, EMPHATIC and DsTau/NA65 experiments are in the midst of program of measurements aimed at improving flux determination at these beamlines. Additionally, upgrades to the Fermilab accelerator complex [5, 108] will enable new proton beam dump facilities at PIP II (PIP2-BD [104]) and the SBN (SBN-BD [105]).

Potential future opportunities with focused beams include time-bunched sources, in which a tightly-bunched proton beam and precision timing detectors can be used to separate a wide-band neutrino beam into narrower components by selecting events based on their time of arrival at the detector [109, 110], and optimization of beams to generate higher energy neutrinos allowing for more precise measurements of ν_τ appearance. Another opportunity is ENUBET [111].

8.3.2.2 Neutrinos from Stopped-Pion Sources

Spallation neutron sources provide, as a by-product, the most intense accelerator-based sources of neutrinos in the world, and are particularly important for a wide variety of neutrino physics measurements, including short-baseline oscillations, neutrino interaction studies relevant for oscillation searches at both short- and long-baseline, CEVNS and related new physics searches involving non-standard neutrino interactions, and probes of dark matter using nearby neutrino detectors. These physics measurements are also possible at dedicated, non-spallation-neutron facilities.

Neutrinos from stopped-pion sources have the advantage of fluxes with well-known energy, flavor and time dependence. The dominant flavor components (in some cases dominant to the extent of very high purity) of the flux are ν_μ with precisely known energy of 29.8 MeV from the two-body π^+ decay at rest, followed on a 2.2-μs timescale by ν_e and $\overline{\nu}_\mu$ from the three-body muon decay at rest. More tightly pulsed proton-on-target beams are favorable, as are large and dense targets that stop a high fraction of pions produced, resulting in a well-understood decay-at-rest spectrum. Neutrino production per power is maximized for protons of around 1.3 GeV [112]. Several existing and new facilities are planned, including at the Oak Ridge National Laboratory Spallation Neutron Source (site of COHERENT [85]), for which an update to a total power of 2.4 MW including a Second Target Station is planned [113], J-PARC (site of running JSNS2 [114] and planned JSNS2-II), and the European Spallation Source.

8.3.2.3 Nuclear Reactors

Nuclear reactors have had a central role in experimental neutrino physics ever since the discovery of these elusive particles in 1956. As neutrino sources, they have the following advantages:

- Intensity: about 2×10^{20} electron antineutrinos are produced every second from a 1 GW (thermal) commercial reactor core. They are in fact the most intense artificial source of neutrinos.
- Availability: there are currently over 400 nuclear reactors in operation in more than 30 countries worldwide. The world's nuclear power capacity continues to increase steadily, with about 55 new reactors currently under construction.
- Flavor purity: antineutrinos are produced from the beta decays of nuclear fission products through the $n \to p + e^- + \overline{\nu}_e$ reaction. Consequently, only electron antineutrinos are emitted.
- Predictability: The various flux anomalies non-withstanding, reactor neutrino fluxes are known in both rate and shape to within about 5%. This fact, combined with a very well known detection cross section for inverse beta decay, allows for precision physics studies.
- Cost-effectiveness: researchers do not typically have to bear the costs involved in designing, building, and operating nuclear reactors, whose primary goals include power generation (commercial reactors) and neutron production (research reactors). This in turn allows for small experiments with low barrier to entry and faster timescales from design to data-taking compared to large international projects, providing important opportunities for workforce development.

Nuclear reactors continue to be widely used as MeV-scale neutrino sources and a next-generation reactor neutrino program spanning a wide range of physics goals is under preparation. These experiments will benefit from the precise characterization of reactor neutrino fluxes made by experiments in the last decade, which uncovered discrepancies with the models while also providing important clues about their origin. Direct neutrino measurements with greater precision, as well as in the uncharted region below the 1.8 MeV

inverse beta decay (IBD) threshold, are anticipated in the next decade that will further enhance existing constraints on reactor neutrino emission. The reactor neutrino community is also interested in pursuing ancillary nuclear physics measurements that will allow to fully resolve existing data vs. model discrepancies and that will enable improved reactor neutrino flux modeling.

8.3.2.4 Neutrinos from the LHC

The FASERnu collaboration [115, 116] recently reported the first observations of neutrinos from a collider [117]. This measurement is likely to be the first of many neutrino measurements at the Large Hadron Collider (LHC). Physics goals for LHC-based neutrino experiments include cross section measurements of all neutrino flavors at previously unmeasured neutrino energies, searches for BSM physics, and neutrino flux measurements as novel constraints to LHC event generators [63, 70, 118].

8.3.2.5 Novel Neutrino Sources

Muon-based neutrino sources offer advantages over traditional hadron-focused neutrino beams in that they contain equal parts muon neutrinos and electron antineutrinos and have a well known energy spectrum and flux. Several facilities have been proposed to produce and make use of neutrinos from stored muons. Because they share common challenges associated with producing, accelerating, and storing muon beams, there are many overlaps in R&D efforts towards these facilities. Addressing these challenges was not identified as a priority in the 2014 P5 report, but was set as a high priority in the 2020 update of the European Strategy for Particle Physics. Continued development of these concepts would greatly benefit from an endorsement in the upcoming P5 process. Three stages in the development of stored muon beams can be identified. The first stage is the nuSTORM facility [119], storing 1-6 GeV muons and producing beams of muon and electron neutrinos spanning the 0.5 - 5 GeV energy range without any muon cooling. Its primary physics goal is measurement of electron and muon neutrino cross sections at the few percent level, but it would also provide measurements of various nuclear effects, searches for sterile neutrinos, and serve as a test facility for the development of a future neutrino factory and/or muon collider. Both Fermilab and CERN would be capable of hosting nuSTORM.

A step beyond nuSTORM would be a neutrino factory storing muons in the 5-50 GeV energy range with muon cooling [120]. A key feature of a neutrino factory is the ability to produce a well-understood high-energy neutrino beam. As such, it would provide high-precision measurements of oscillations to tau neutrinos, opening up new tests of the three-flavor mixing paradigm that are not currently possible. It would have greater precision in the measurement of δ_{CP} than DUNE or Hyper-K and would facilitate a wide variety of searches for BSM at both the near and far detector. The final stage then would be TeV-scale muon collider with full 6D muon cooling. If a muon collider is part of the portfolio of future colliders within the energy frontier, then both NuSTORM and a neutrino factory would be useful R&D platforms.

Cyclotrons represent another novel artificial source of neutrinos [121,122]. The IsoDAR experiment [123] will utilize a high power (600 kW) cyclotron to produce a 60 MeV proton beam [124]. Beam interactions with a beryllium target create an intense source of neutrons which subsequently enter a surrounding ^{7}Li sleeve, thermalize, and then capture on ^{7}Li to create the high-Q beta-decay isotope ^{8}Li. The resulting beta decay ($\tau_{1/2}$ = 839 ms) produces a high-energy, single-isotope electron-antineutrino source (mean antineutrino energy of 6.4 MeV) with 1.15×10^{23} $\overline{\nu}_e$ expected in four years of livetime [125]). While IsoDAR represents a unique source that can be paired with a number of existing and future large underground free-proton-based (e.g. H_2O, CH_2) detectors, the current plan is to pair IsoDAR with the 2.3 kton liquid scintillator detector at Yemilab in South Korea. The resulting detected 1.7 $\times 10^6$ IBD and 7000 $\overline{\nu}_e + e^-$ elastic events

in four years of running will provide leading sensitivity to electron-flavor disappearance, non-standard neutrino interactions, and exotic particle production, among other physics measurements [125, 126]. The IsoDAR@Yemilab cavern excavation has recently been completed and the experiment is now at an advanced R&D stage. Cyclotron-based sources have additional broader impacts [127].

8.3.3 Detectors

Neutrino physics spans an enormous range of energies and scales: from detection of low-energy cosmic neutrinos, to keV-scale recoils in coherent neutrino scattering, to MeV-scale solar, reactor, and neutrinoless double-beta decay events, to GeV and TeV-scale detection of neutrinos from accelerators and the atmosphere, and beyond with cosmic sources in the PeV–ZeV range. While any particular experiment tends to focus on just one or two detection approaches, the great breadth of neutrino physics means that there is an equally broad spectrum of detection technologies and methodologies.

At any one time, there are a dozen or more medium- to large-scale neutrino detectors operating worldwide, several more in the design or construction phases, and many future detectors planned. Beyond this are the diverse set of small- to medium-scale prototypes distributed across universities and labs. The focus in this section of the report is on new technologies and approaches that will enable future neutrino detectors, and thus experiments that are already built and running, or are under construction or for which technical designs exist are not discussed in great detail.

While there are many exciting detectors and enabling technologies for future neutrino experiments (many of which are described in detail in the NF10 report and associated white papers), there are a few ideas that have had a particularly large community interest:

- **Broadening the Noble Liquid and Gas Physics Program:** Many ideas are being pursued for improving liquid and gaseous TPCs, including new charge readout technologies, background reduction and analysis techniques for low-energy physics, the use of underground argon for low-background physics [128], and the use of various dopants (xenon, photo-ionizing dopants) to increase photon or charge yields, or light traps like the ARAPUCAs for improved light detection. Many of these ideas may enable a broader physics program than can be done with existing detector designs.
- **Pursuit of hybrid Cherenkov/scintillation Detectors:** Many different technologies are being developed for these, including water-based liquid scintillator, slow fluors, fast timing with large area picosecond photodetectors (LAPPDs) and other devices, and spectral photon sorting with dichroicons. At very large scales like the proposed Theia detector, these could have very broad physics programs.
- **Optimizing low-threshold neutrino detectors:** The work here aims to expand the ever-growing CEvNS program and to fully exploit the physics reach of CEvNS in the next decade. It includes not just lowering energy thresholds but improving background rejection techniques, understanding detector responses at the eV-scale, and moving toward larger detector masses. Enabling technologies have many synergies with direct neutrino mass measurements and recoil-imaging directional dark matter detectors.
- **Developing Technologies for Neutrino Detection at the PeV Scale and Beyond:** Observations of high-energy neutrinos at large-neutrino telescopes has provided a wealth of physics and multi-messenger astrophysics, and new opportunities for studying neutrino interactions at LHC, including possibly tagging the production vertex, are particularly exciting. Technologies for ν telescopes include radar echo detection, Askaryan effect detection, and ever-larger scale optical

detection, while at the LHC they include picosecond timing synchronizations, intelligent triggering, and high-resolution tracking.

- **Co-development of neutrino and dark-matter detectors:** Both the development of new noble liquid and gas detectors and low-threshold detectors of various technologies lend themselves to development of enabling technologies that are useful for both the Neutrino Frontier and the Cosmic Frontier.

Liquid Noble and Gas Detectors Since the last Snowmass, there has been enormous progress and diversity in detectors that use either noble liquids or gases as their target material. Such detectors have been used for dark matter searches by experiments like DarkSide, DEAP, and LZ, for neutrinoless double-beta decay with experiments like EXO-200, and as part of both the short-baseline program at FNAL with MicroBooNE, SBND, and ICARUS, and the DUNE experiment at SURF. There are many new ideas for doing more with these detectors, from scaling to larger mass (e.g., nEXO [129]), to improving reconstruction capabilities by using pixelated charge readout in LArTPCs (e.g., LArPix, QPix) or moving to high-pressure (e.g. ND-GAr [14], NEXT) or atmospheric-pressure (e.g. CYGNUS) TPCs, to lowering thresholds by using underground sources of LAr. There is also interest in new approaches to detecting scintillation light in these detectors, including pixelated SiPM arrays, photo-ionizing dopants, or by increasing light coverage with ARAPUCA light-traps deployed on TPC cathodes using power-over-fiber. A common theme in the LArTPC community is the pursuit of a broader physics program than currently planned, including low-energy solar neutrinos or neutrinoless double-beta decay [130, 131], much of which would be leveraged by underground or low-background argon [132].

Thus some of the highest technical priorities in this area are:

- Larger-scale production of underground argon sources, or ways to remove ^{39}Ar and ^{42}Ar.
- Development of pixelated charge readout TPCs.
- Development of pixelated light readout for TPCs.
- Investigations of new ways for photon detection in liquid noble detectors, including photo-ionizing dopants.
- Advanced triggering schemes at low-energies, including machine learning techniques.

Photon-Based Detectors Neutrino Detectors that use photons as their primary carrier of neutrino interaction information have a very successful history in neutrino physics. They include Cherenkov detectors like IMB, Kamiokande, SNO, and Super-Kamiokande, and scintillation detectors like KamLAND, Double CHOOZ, Daya Bay, RENO, BOREXINO, NOVA, PROSPECT [133], and SNO+. Of particular interest in the past decade or so are *hybrid* Cherenkov/ scintillation detectors, which can detect and discriminate between Cherenov and scintillation photons ("chertons" and "scintons") in the same detector, thus allowing a very broad neutrino physics program. Enabling technologies that would allow this have been and continue to be developed over the past decade [134], including new materials like water-based liquid scintillator and slow fluors, new and faster devices like LAPPDs, and spectral photon sorting with devices like dichroicons. These new technologies, employed either separately or in concert, make large-scale hybrid detectors a real possibility. The most developed of these ideas is the proposed Theia experiment, which could sit in the LBNF beam at SURF.

In addition to hybrid Cherenkov/scintillation detectors, new ideas for segemented detectors have also been developed. The most developed of these is LiquidO, which would use scintillator with short scattering

lengths and an array of fiber optics to create a "self-segmented" detector that could allow precision track reconstruction at both high and low energies. The SLIPS idea, which removes physical segmentation by floating a scintillator volume, could allow very low-background experiments by eliminating radioactive sources in the volume.

Looking even further ahead, some of the highest technical priorities seen in this area, which could be explored between this Snowmass and the next, are:

- Lower-cost, large-area high-quantum efficiency $\sim 40\%$ photon sensors.
- Lower-cost, fast timing ($\sim$ 100 ps) photon detectors.
- Dichroic filters that can be deposited on non-flat surfaces and with sharper cut-on/cut-off curves, even at high incidence angles.
- Narrow-band fluors for liquid scintillators.
- High-yield scintillators with attenuation lengths > 40 m.
- High-yield "slow" ($\sim$ 10 ns risetime or longer) fluors.
- Low-background fibre optics.
- New approaches to radiologic background. reductions, beyond levels seen in Borexino.

Low-Threshold Neutrino Detectors The development of low-threshold neutrino detectors with eV-scale resolution has become a priority in neutrino physics during the last decade since it has opened up new portals for the study of neutrino properties and the search for new physics. The COHERENT program has pioneered the use of detector technology which enabled the first observation of CEvNS and is driving since then a blooming new research field under U.S. leadership. This technological breakthrough triggered R&D activities worldwide of low-threshold neutrino detectors based on a wide range of technologies (e.g. [69,135–137]). A broad and complementary CEvNS program based on small-scale experimental projects will enable precision measurements and pave the way for applications. The community will profit from multiple technological synergies with dark matter search measurements and a variety of proposed approaches. To achieve the technological goals the following challenges have to be addressed:

- Improve detector thresholds towards the eV scale.
- Develop advanced techniques for suppressing backgrounds, including the community-wide observed low-energy excess.
- Establish multiplexing techniques to scale up active detector mass.
- Understand the detector response at the eV scale.
- Increase level of automatization for applications in science, industry, and for society.

Exploiting the strong technological interconnections with direct dark matter searches and neutrinoless double-beta decay is essential and of mutual interest for both communities. The CEvNS community will profit from the ongoing R&D efforts on low-threshold directional recoil detectors for DM searches [136]. Multi-ton dark matter detectors will play a crucial role for the measurements of solar and supernova neutrinos in the next decade [138].

High-Energy and Ultra-High-Energy Neutrino Detectors Detection of neutrinos at the TeV scale and beyond [139] has been pioneered by big neutrino telescopes like IceCube and KM3NeT. The physics and astrophysics and multi-messenger possibilities from these detectors is remarkably broad, and these detectors have been exceptionally successful. Future plans for these detectors focus on moving toward even higher energies, into the EeV and ZeV regimes, which require scales going well beyond km^3 or new technologies, exploiting the Askarayan effect or radar echoes off ionization trails. In many cases, the enabling "technology" for these telescopes is a piece of geography: polar or Greenland ice sheets, mountain ranges that can be used as targets, etc. At the same time, there is a new opportunity at the LHC with the FPF [63, 70] to detect neutrinos produced in collisions, perhaps with the possibility of tagging the neutrino production vertex in a collider detector.

High priorities over the next several years for these detectors are:

- Develop further the ability for sensitive radio detection of neutrinos interacting in ice or the atmosphere.
- Demonstrate at larger scales the detection of neutrinos via radar echos off ionization cascades.
- Create low-cost ways of scaling to ever-larger telescopes sizes.
- Create intelligent triggers for background rejection at the FPF.
- Create larger-scale high-resolution tracking options for FPF neutrino events.

8.3.4 Facilities

Key to success of the experimental programs underway and planned in the Neutrino Frontier is the availability of suitable facilities. These have been primarily provided at national laboratories, with some experiments hosted by universities. Of special importance for the Neutrino Frontier are underground facilities. Because neutrino events are typically of low rate, cosmic rays are often a significant background, and overburden for cosmic ray shielding is either absolutely required or highly desirable, even in the case of pulsed-beam experiments for which background can be reduced by timing. Large, multipurpose neutrino experiments require very large cavities and have specific requirements depending on the detector type. Notably, DUNE has special requirements to accommodate 40 kton of liquid argon. The Underground Facilities Frontier report provides more details [140]. Additional ideas for new facilities have been proposed as well [141].

8.4 Applications and Community Engagement

8.4.1 Applications

In addition to the pursuit of fundamental knowledge, investment in scientific discovery is also motivated by the development of technologies and the training of a skilled workforce that can benefit society in other ways. In the case of Neutrino Physics, there are many instances of this dynamic playing out. But somewhat surprisingly, given the inherent difficulty of neutrino detection, the direct application of neutrinos to advance other fields of research or solve societal problems is also a possibility. Examples of direct neutrino applications include monitoring of nuclear reactors for safeguards and non-proliferation [142] and

the probing the Earth's interior via its neutrino emissions [143] and tomography [144,145]. There are strong synergies between the neutrino physics topics of community interest developed through this Snowmass process and direct neutrino applications. These synergies can take the form of overlapping needs in terms of technology development, workforce capabilities, facilities, and underlying scientific knowledge [146–148]. Specific examples of synergies highlighted during Snowmass include the following:

- Improved knowledge of the reactor neutrino emissions (flux and spectrum) is needed for reactor monitoring applications and would enable reactors neutrinos to continue to be a tool for discovery [147, 149, 150].
- Neutrino detectors using the inverse beta decay or CEvNS channels with improved background suppression operating close to reactors can help to address neutrino anomalies, probe BSM physics, and provide versatile monitoring capabilities [147].
- Technologies that could reduce the cost and improve the performance of large inverse beta decay neutrino detectors could provide reactor monitoring at larger distances and address a wide range of neutrino physics topics [65, 151].
- Projects at the intersection of neutrino physics and neutrino applications can provide broad training opportunities for community members while also opening new career pathways.

The fact that technologies and workforce capabilities developed by the field of neutrino physics can have benefits in many other areas of science and society provides an additional motivation for societal investment. To further advance our field in this respect, it is important that community members have such possibilities in mind and actively seek opportunities to highlight the broader impact of their research. It is also critical to note that the full impact of neutrino applications can only be realized through early and attentive engagement with experts from potential end-user communities [148]. Given the strong synergies between neutrino physics and neutrino applications noted above, it is apparent that stakeholders from both neutrino and end-user communities would benefit from further coordination. This could take the form of joint investment in detector R&D efforts, measurements to improve our knowledge of reactor emissions, and/or reactor-based experiments and demonstrations.

8.4.2 Community Engagement

Given that neutrino physics represents a major component of the U.S. program, there are opportunities for leadership in addressing societal issues. Additionally, the widely varying scope of activities within the Neutrino Frontier requires significant collaboration across disciplines and sectors. Commitment to community engagement, including discourse with other scientific disciplines, a diverse and welcoming environment within HEP, and education and outreach, facilitates these necessary collaborations. It is therefore critical for the community to address issues of diversity, equity and inclusion. A work environment that is welcoming to all is intrinsically desirable, conducive to scientific productivity, and necessary to attract and retain the people at the heart of our program. A strong outreach and education component to the program is also crucial for attracting the best talent to the particle physics community as well as for communicating the impact of our neutrino physics. The Neutrino Frontier facilities have a significant impact on the surrounding communities, so it is important to be good citizens of those communities.

While DEI and community engagement is the responsibility of everyone in the field, host laboratories for large experiments have important leadership roles to play.

The fact that this section comes late in this report does *not* mean that it is an afterthought. We emphasize the overarching importance of community engagement for the overall success of neutrino physics and HEP as a whole. This is the first Snowmass in which Community Engagement has been identified as a Frontier. Challenges have arisen, mirroring those that many in the field experience in their day-to-day work and at their home institutions, as participation in the Community Engagement Frontier is often perceived as in conflict with or competing with effort in the scientific Frontiers. As a field we must find a way to reinforce the concept that Community Engagement is a necessary part of our work, rather than a volunteer effort that a few people do on the side. A cohesive, HEP-wide strategic plan that provides support, rewards, and career development paths for this work is urgently needed [152].

8.5 Long-Term Outlook

If the three-flavor paradigm is sufficient to fully describe the neutrino sector, it will take approximately the next two decades to fill in the main features of the picture. After that, precision measurements will be needed to continue to test the robustness of the paradigm. However, Nature may very well have surprises for us, and we need a program that will allow us to explore broadly and flexibly, if one of the current anomalies persists in pointing the way to new physics, or if perhaps some entirely new BSM signature makes an appearance. It is difficult to determine detailed road-map for neutrino physics more than two decades out. Nevertheless, we need to prepare for potential opportunities in a post-DUNE era with a broad and robust program of instrumentation development. We describe in this section some longer-term prospects that align with the philosophy of broad exploration and readiness to pursue higher precision and new directions should the data lead us there.

Future neutrino facilities, by design, should offer a wide range of opportunities to explore BSM physics within and outside the neutrino sector, without interfering with the measurement of neutrino oscillation parameters. Thus, it will be vital to significantly enhance the potential of these facilities by keeping BSM searches as a high priority in the design and optimization of future experiments. These efforts must include not only detector capabilities that will strengthen the signal efficiencies, but also new beamline designs that could enhance the signal-to-background ratio, in particular for backgrounds from neutrino interactions, in order to ensure the co-existence of BSM physics with precision neutrino property measurements. In addition, in order to pursue BSM physics more effectively, enhanced numerical tools will be needed for accurate signal simulation and to understand the expected backgrounds precisely. This will require a close collaboration with other particle physics frontiers and the nuclear physics community.

The rich and diverse program that is underway or projected for the upcoming P5 period promises to provide a comprehensive understanding of the short-baseline neutrino anomalies. This will play a crucial role in the long-term neutrino program, as the phenomenology behind the anomalies will have an increasing impact in the interpretation of future neutrino measurements as their precision improves. Irrespective of what is discovered, be it new physics or conventional explanations for the anomalies, the community will be compelled to explore, develop, and support opportunities for incorporation of that understanding in the interpretation of future results, or else to develop a program of new dedicated measurements at those facilities aiming to characterize non-standard phenomena with high precision. Additionally, the upcoming P5 period provides opportunities for the development of new synergies across topics within multiple frontiers (colliders, dark matter, astrophysics, cosmology, instrumentation) that can be explored in the following decade and beyond.

The motivation for astrophysical neutrino detection extends to the indefinite future – neutrino messengers from the sky will always have something to tell us. Large-scale, multi-purpose detectors are likely to dominate the future for both low- and high-energy neutrino astrophysics and will guarantee an unprecedented view

of natural sources. Detectors such as the proposed DARWIN, RES-NOVA, and Theia can address multiple topics such as searches for neutrinoless double-beta decay and dark matter, as well as astrophysical neutrino detection. Neutrino telescopes using optical and radio detection techniques, such as IceCube-Gen2, GRAND, and POEMMA will probe neutrino properties at energies not accessible in the laboratory and will enable the study of the most extreme systems in our Universe. At the same time, urgent efforts are required to model (non-)standard physics in astrophysical sources to take advantage of the upcoming plethora of multi-messenger datasets. Future neutrino detectors that look beyond DUNE will allow precision probes of the three-flavor mixing model, and will also the broaden the physics programs of large detectors. One example would be a very large LArTPC filled with clean, underground argon, with charge- and light-sensitive pixels, or doped with photo-ionizing materials, to do a broad range of low-energy physics. Loaded with enriched LXe, such a detector could also look for neutrinoless double-beta decay with sensitivity below the inverted ordering region. These next-generation LAr detector ideas go by different names, such as "SLoMo", "SoLAr", and "LArXe." Another idea is the proposed Theia detector, which is a hybrid Cherenkov/scintillation detector that could do precision measurements of very low-energy solar neutrinos, diffuse supernova neutrino detection, perform searches for sterile neutrinos, and also push well beyond DUNE in precision tests of the three-flavor mixing model (including, for example, studies of the second oscillation maximum). On the low-threshold side, much will depend on what the next generation of CEvNS detectors will see, but it is clear that detectors with (sub-)eV thresholds will bring reactor, accelerator, and solar neutrino experiments into a higher-precision era. Should a signal of new physics be seen in the upcoming generation of experiments, it is anticipated that a push for higher-statistics detectors with even more precise understanding will be needed.

In the long term, opportunities exist to use current artificial neutrino sources to pursue new physics goals, such as optimizing focused-hadron sources for tau neutrino oscillation. There are also many exciting opportunities with new sources capable of producing more intense and/or precisely characterized beams, which can enable improved measurements of neutrino properties and searches for beyond-the-Standard-Model physics. These include compact cyclotron electron anti-neutrino sources and muon-based sources, which could ultimately result in a neutrino factory, which would have significant synergies with a muon collider program.

8.6 Conclusion

In summary, the U.S. neutrino program is poised for an exciting future. The path is clear for the next P5 period and the decade beyond it. DUNE is the flagship international experiment that will fill in the gaps of the three-flavor picture and explore new BSM territory, as well as be open to astrophysical signal opportunities from the skies. Beyond DUNE, the neutrino community has sent a clear message that a broad neutrino program across scales, connecting to other Frontiers and fields, is highly desirable for maximizing science output for the field. Theoretical efforts are a key component of the program, and development of new technologies is critical for the long-term future. As a final point, physics is done by humans. We will not fully succeed in our science without making diversity, equity, and inclusion efforts an integrated, high-priority component of our work.

3.A Appendix: Data on Experimental Programs

Experiment name	Status	Year	Physics goal	Ref.
Soudan II	Data Taking/Complete	1983	Atmospheric neutrino oscillations, search for proton decay and neutron-antineutron oscillations, muon astronomy	[153]
Super-Kamiokande	Data Taking/Complete	1996	Atmospheric and solar neutrinos, supernova neutrinoK burst, diffuse supernova neutrinos, indirect dark matter, proton decay, far detector for T2K	[154]
TEXONO	Data Taking/Complete	2002	Magnetic moments (completed 2007), nu-electron cross-section (completed 2011), dark-matter searches (completed 2014), nu-Nucleus coherent elastic scatter (since 2013), Beyond Standard Model Physics (since 2014)	[155]
MINOS	Data Taking/Complete	2005	Studies of neutrino oscillations and related processes	
EGADS	Data Taking/Complete	2009	Supernova neutrinos, Gd-H2O technology demonstrator	[156]
MINERvA	Data Taking/Complete	2010	Precision measurements of neutrino interactions on a variety of nuclei	[157]
T2K	Data Taking/Complete	2010	Neutrino oscillation, searches for exotic physics, and measurements of neutrino interactions	[158]
Daya Bay	Data Taking/Complete	2011	Oscillations (precision measurement of θ_{13} mixing angle and atmospheric mass splitting), search for sterile neutrinos, characterization of reactor antineutrino emission, searches for new physics	[159]
Double Chooz	Data Taking/Complete	2011	Neutrino Oscillation (measurement of θ_{13}) and Neutrino Reactor (IBD mean cross-section per fission)	[160]
MINOS+	Data Taking/Complete	2013	Studies of neutrino oscillations and related processes (using NOvA-tuned NuMI beam)	[161]
NOvA	Data Taking/Complete	2014	Neutrino oscillations, in particular mass ordering , CP violation, and octant. Steriles. Neutrino Cross sections. Cosmic ray and astrophysical sources studies	
LArIAT	Data Taking/Complete	2015	Hadron scattering measurements on argon target	[162]
MicroBooNE	Data Taking/Complete	2015	Sterile neutrinos, BSM searches, neutrino interaction measurements, demonstration of liquid argon technology	[163]
The MAJORANA DEMONSTRATOR	Data Taking/Complete	2015	Neutrinoless Double-Beta Decay, Dark Matter Searches	
STEREO	Data Taking/Complete	2016	Sterile neutrino, 235U fission spectrum	[164]
NA61/SHINE	Data Taking/Complete	2016	Hadron production measurements for neutrino beams	[165]
CUORE	Data Taking/Complete	2017	Neutrinoless double-beta decay	[166]
PROSPECT-I	Data Taking/Complete	2018	Sterile neutrino (BSM), Reactor Flux and Spectrum, Boosted Dark Matter, Detector Technology Development	[167]
BeEST	Data Taking/Complete	2019	KeV Neutrino Search	[168]
NINJA experiment	Data Taking/Complete	2019	Neutrino cross-section measurement, sterile neutrino search	[169–173]

continued on the next page

Table 8-4. *Table for Neutrino Frontier experiments. Information in this table was provided by the collaborations.*

Experiment name	Status	Year	Physics goal	Ref.
KATRIN	Data Taking/Complete	2019	Neutrino mass, sterile neutrino, relic neutrinos, BSM	[75]
JSNS2	Data Taking/Complete	2020	Sterile neutrino, neutrino xsec, exotic searches	[114]
SNO+	Data Taking/Complete	2020	Double beta decay, reactor and geo antineutrinos, solar neutrinos	[174]
SND@LHC - Scattering and Neutrino Detector at the LHC	Data Taking/Complete	2021	TeV neutrino interactions, lepton flavor universality, heavy flavor production in the forward region	[175]
e4nu	Data Taking/Complete	2022	Oscillation	[90]
ICARUS at SBN	Data Taking/Complete	2022	Sterile neutrino, dark matter, neutrino cross section, other BSM	[176]
IceCube Neutrino Observatory	Approved/Under construction	2005	High energy neutrino astrophysics. Neutrino oscillations. Sterile neutrinos. Indirect search for Dark Matter	[177]
JLab E12-14-012	Approved/Under construction	2017	Measurement of inclusive and exclusive cross sections for argon and titanium. Extraction of the spectral functions from the exclusive data	[178]
FASER	Approved/Under construction	2019	Cross sections at TeV energies, lepton universality, forward charm production	[115, 117]
NuDot	Approved/Under construction	2019	Double-beta Decay; Liquid scintillator R&D	[179]
LEGEND-200	Approved/Under construction	2022	Neutrinoless double-beta decay; dark matter searches; other BSM physics	[180]
NEXT-100	Approved/Under construction	2022	Neutrinoless double beta decay	[181]
SBN - Short-Baseline Neutrino Program at Fermilab	Approved/Under construction	2022	Sterile neutrinos, neutrino interactions, BSM searches	[176]
nEXO	Approved/Under construction	2022	Neutrino-less Double Beta Decay	[182]
NUCLEUS construction	Approved/Under	2023	CEvNS at reactors, non-proliferation	[183]
Jianmen Underground Neutrino Observatory (JUNO)	Approved/Under construction	2023	Neutrino mass ordering, precision measurement of three oscillation parameters, solar neutrinos, geoneutrinos, atmospheric neutrinos, measurement of reactor antineutrino spectrum, proton decay, searches for BSM physics (possibly extending to neutrinoless double-beta decay in a second phase)	[184]
SBND	Approved/Under construction	2023	Sterile neutrinos, neutrino interactions, BSM searches	[185]
Ricochet	Approved/Under construction	2023	Neutrino coherent scattering from reactor neutrinos, beyond standard model searches	[69]
Water Cherenkov Test Experiment	Approved/Under construction	2024	Pion scattering, secondary neutron production, water Cherenkov detector response	[186]

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Table 8-5. *Table for Neutrino Frontier experiments, continued. Information in this table was provided by the collaborations.*

Experiment name	Status	Year	Physics goal	Ref.
IceCube Upgrade	Approved/Under construction	2026	Neutrino Oscillations, Indirect dark matter search, astrophysics	[187]
Hyper-Kamiokande	Approved/Under construction	2027	Neutrino oscillations (CP violation, mass hierarchy etc), Nucleon Decays, Neutrino Astrophysics	[188]
DUNE	Approved/Under construction	2029	CP violation, mass ordering, precision oscillation physics, Supernovae, solar neutrinos, sterile neutrinos, precision tests of 3-flavor paradigm, nucleon decay, direct DM detection, other BSM searches	[9]
LiquidO	Concept/R&D	2013	Technology envisaged for neutrino physics in general above. 1 MeV	[189]
COHERENT	Concept/R&D	2014	Neutrino scattering, BSM searches, accelerator-produced sterile dark matter, neutrino electromagnetic moments, oscillations, nuclear structure	[85]
CDEX-300	Concept/R&D	2020	Neutrino mass, CP violation	[190]
NUXE	Concept/R&D	2020	Reactor neutrino CEvNS, neutrino magnetic moment, sterile neutrino	[191]
ANNIE	Concept/R&D	2020	Neutrino interactions, detector R&D	[192]
EMPHATIC	Concept/R&D	2022	Neutrino flux	
ECHo	Concept/R&D	2022	Neutrino mass	[193]
HOLMES	Concept/R&D	2022	Neutrino mass	[194]
Modern Modular Bubble Chamber LDRD	Concept/R&D	2022	Broad terms are to take measurements of neutrino cross sections	[195]
FASERnu	Concept/R&D	2022	TeV neutrino interactions	[63, 115, 158]
PROSPECT-II	Concept/R&D	2023	Sterile neutrino (BSM), Reactor Flux and Spectrum, Boosted Dark Matter, Detector Technology Development	[133]
LEGEND-1000	Concept/R&D	2024	Neutrinoless double-beta decay; dark matter searches; other BSM physics	[180]
PALEOCCENE	Concept/R&D	2024	CEvNS at reactors, dark matter, non-proliferation	[135, 196]
IceCube-Gen2	Concept/R&D	2025	Neutrino astronomy, supernovae, cosmic rays, atmospheric neutrinos, neutrino oscillations, sterile neutrinos, neutrino interactions	[197]
SBC-CEvNS	Concept/R&D	2025	Reactor CEvNS	[198]
FLArE	Concept/R&D	2026	TeV neutrino cross-section, lepton flavor universality, matter heavy flavor production in the forward region, dark matter direct detection, milli-charged particles	[63, 158]
LDMX	Concept/R&D	2026	EN scattering, dark matter searches	[199]
FASERnu2	Concept/R&D	2026	TeV neutrino cross-section, tau neutrinos, lepton flavor universality, heavy flavor production in the forward region	[63]
AdvSND - Advanced Scattering and Neutrino Detector at the LHC	Concept/R&D	2026	TeV neutrino cross-section, lepton flavor universality, heavy flavor production in the forward region	[63, 158]

continued on the next page

Table 8-6. *Table for Neutrino Frontier experiments, continued. Information in this table was provided by the collaborations.*

Experiment name	Status	Year	Physics goal	Ref.
NEXT-HD	Concept/R&D	2026	Neutrinoless double beta decay	[200]
IsoDAR	Concept/R&D	2027	Sterile neutrino, weak mixing angle, non-standard neutrino interactions, light X particles	[201, 202]
Project 8	Concept/R&D	2028	Neutrino mass scale with aimed sensitivity of 40 meV/c^2.	[77]
CDEX-1T	Concept/R&D	2028	Neutrino mass, CP violation	[190]
NEXT with barium tagging	Concept/R&D	2028	Neutrinoless double beta decay	[203]
TAMBO: Tau Air-Shower Mountain-Based Observatory	Concept/R&D	2030.	Make precision measurements of high-energy astrophysical tau neutrinos	[205]
Trinity	Concept/R&D	2030	Astrophysical neutrinos, oscillations, bsm	[206]
nuSTORM and BSM searches	Concept/R&D	2030	Neutrino interactions an cross sections, sterile neutrinos,	[207]
Theia	Concept/R&D	2030	CP violation, neutrinoless double beta decay, CNO solar neutrinos, 8B solar neutrino spectrum, precision geoneutrino flux, nucleon decay, supernova neutrinos, DSNB, sterile neutrinos	[208]
CUSO (Case Underground Salt Observatory)	Concept/R&D	2032	Solar neutrinos, geoneutrinos, 0vbb	[209]
The Giant Radio Array for Neutrino Detection (GRAND)	Concept/R&D	2032	Ultra high energy neutrino detection, ultra high energy neutrino cross sections, astrophysics	[210]
CUPID-1T	Concept/R&D	2035	Neutrinoless double-beta decay	[79]
European Spallation neutrino Super Beam (ESSnuSB)	Concept/R&D	2037	CP violation, cosmological neutrinos, sterile neutrinos, proton lifetime	[106]
SBN-BD (SBN Beam Dump Experiment)	Concept/R&D	2039	Accelerator-produced dark matter, sterile neutrino	[105]
PIP2-BD (PIP-II Beam Dump Experiment)	Concept/R&D	2039	Accelerator-produced dark matter, ALPs, testing short-baseline neutrino anomalies, precision tests of the SM, neutrino-nucleus cross sections	[104]

Table 8-7. *Table for Neutrino Frontier experiments, continued. Information in this table was provided by the collaborations.*

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9

Rare Processes and Precision Measurements Frontier

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Executive Summary

Motivation and Big Questions

The Rare Processes and Precision Measurements Frontier, referred to as the "Rare and Precision Frontier", or RPF, encompasses searches for extremely rare processes or tiny deviations from the Standard Model (SM) that can be studied with intense sources and high precision detectors. Our community studies have identified several unique research opportunities that may pin down the scales associated with New Physics (NP) interactions and constrain the couplings of possible new degrees of freedom. Studies of rare flavor transition transitions and precision measurements are indispensable probes of flavor and fundamental symmetries, and provide insights into physics that manifests itself at higher energy or through weaker interactions than those directly accessible at high-energy colliders.

The Frontier explores the following fundamental topics:

- the origin of quark and lepton flavor, generations, and mass hierarchies;
- the exploitation of flavor (both quark and lepton) as a precision probe of the Standard Model;
- the use of flavor physics as a tool for discovering new physics;
- the origin of the fundamental symmetries and their breakdown mechanisms;
- the physics of the dark sector available at high-intensity machines;
- the origins of baryon and lepton number violation, through the investigation of processes such $0\nu\beta\beta$ decays, proton decays, or baryon-antibaryon oscillations

- searches for non-zero electric dipole moments (EDMs) and CP-violation as well as fundamental (for example, Lorentz) symmetry tests;

- the ways in which non-perturbative Quantum Chromodynamics (QCD) explains the rich landscape of hadron spectroscopy, including both conventional and exotic hadrons.

The opportunities presented in this report form an open ecosystem with intertwined research goals. These goals are motivated by the Particle Physics Projects Prioritization Panel (P5) driver "explore the unknown," which connects all of the physics frontiers. Studies of neutrinos, quarks, and charged leptons provide complementary information, which can lead to a more complete picture of the physics underlying the question of the generations and the different properties associated with the flavor quantum numbers. Why are there three generations of quarks, charged leptons, and neutrinos, and what links the flavor of quarks to the flavor of leptons? Both quarks and leptons have flavor and mix, but the matrices describing the couplings between different flavors, the Cabibbo-Kobayashi-Maskawa (CKM) matrix for quarks and the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) for neutrinos, have different structures. The CKM matrix is highly hierarchical, with the diagonal elements with magnitude close to unity, and progressively smaller off-diagonal elements, as seen in the Wolfenstein parameterization [1]. In contrast, the PMNS matrix has much larger off-diagonal elements. Charged leptons do not mix like quarks in the Standard Model. These patterns of mixing for the charged and neutral fermions are a mystery. The P5 driver "Pursue the physics associated with neutrino mass" does not explicitly mention neutrino flavor or any potential linkage to the quark sector, leaving out a set of crucial questions in neutrino physics. Reaching outside the quarks and leptons, we can also ask, "do leptonic decays of the Higgs violate flavor?"

Flavor plays a critical dual role in high-energy physics. First, the origin of the flavor structure of the Standard Model and various hierarchies of quark and lepton properties have been a fundamental unanswered question since the discovery of the muon. The limits on $\mathcal{B}(\mu \to e\gamma)$ led to the prediction that more than one neutrino species must exist. Rare decays and flavor transitions offer many opportunities to probe the structure of possible new physics. Second, flavor transitions are a powerful tool in constraining (and suggesting) possible models of Beyond the Standard Model (BSM) physics in light of the richness of the observed decay modes. Flavor is thus a common theme across much of the Frontier. Investigating flavor combines theoretical and experimental research pursued through a combination of small, medium, and large experiments that complement and enrich this broad program. Placing all of these closely related topics into a general "explore the unknown" driver captures neither how important they are nor how linked they are, both among themselves and across the Frontiers. In order to capture the unique opportunities provided by the study of physics that distinguishes different flavors, we proposed to introduce a new science driver, *flavor as a tool for discovery*.

Our Frontier also investigates the conservation of baryon and lepton numbers, captured in the P5 driver of "new physical principles." Proton decay and the $\Delta L = 2$ process of neutrinoless double beta decay are shared by the Neutrino and Rare and Precision Frontiers, but this Frontier also examines other baryon and lepton-number violating processes, such as $n\overline{n}$ oscillations.

Another P5 driver was "identify the new physics of dark matter." The Rare and Precision Frontier studies the dark sector using intense beams to discover dark matter (DM) and dark sector particles, generally in the electron-to-proton mass range. The interactions of dark matter particles created by thermal processes with visible matter in the hot early universe could explain its abundance today. We are poised to begin a simultaneously focused and wide-ranging period of exploration, with specialized experiments at colliders, searches in the flavor factories, and dedicated experiments that will either discover such particles or improve the limits by factors of 10 to 1000.

Community Consensus

This report covers many invaluable physics topics, and we encourage the reader to explore them. We have identified seven central points for the broader community (unordered and intertwined):

- We call for a new science driver, *flavor as a tool for discovery*, with two main goals. The first objective aims at uncovering the underlying reason for family replication and their different properties. The second encompasses the systematic study of flavor-specific decays that probe new physics through its interference with SM amplitudes. It is important to note that minimum flavor violation is not necessarily applicable to several plausible NP models. The effort to understand the physics of flavors and generations is central to both physics programs articulated by the Neutrino and Rare Processes and Precision Measurements Frontiers, but this centrality needs to be articulated more clearly.
- The U.S. should support the LHCb Phase-II upgrades and Belle II. These experiments are broad, powerful, and irreplaceable probes of flavor physics along with topics relevant to all the Frontiers. These experiments pursue complementary research programs that utilize different beams and detection techniques to explore a vast array of new physics in beauty, charm, and rare tau decays. In addition, they investigate the patterns of bound states as the manifestation of the richness of QCD in its non-perturbative regime and contribute significantly to the exploration of the dark sector.
- We should select a portfolio of accelerator-based dark sector experiments that are well-motivated, unique, and affordable. Many possibilities have been identified and studied during the Snowmass process. P5 needs to support this physics, with a consequent process through which the community, DOE, and NSF select an efficient and effective subset of the opportunities.
- Experiments investigating charged lepton flavor violation and lepton number violation in the muon sector probe mass scales far beyond the direct reach of colliders, as well as explore the nature of the flavor physics issues core to HEP. PIP-II at FNAL enables a new muon program at an unprecedented intensity that could increase the discovery potential of such experiments by at least an order of magnitude. The U.S. should support a vigorous R&D program towards its realization.
- The theory efforts that guide and enable these investigations, while not a Project, should be vigorously supported by P5. Our Frontier relies on the techniques of and guidance from Effective Field Theories (EFTs). Calculations of quantities throughout the Rare and Precision Frontier rely on computational methods that provide precise and unbiased results that can be systematically improved as needed, such as Lattice QCD. Precision measurements of deviations from the Standard Model, instead of the direct observation of new particles, require these methods' intellectual framework and power. In addition, theory-experiment collaboration in developing new experimental approaches has been at the foundation of much of the progress in dark sector searches and continues to be vital to this growing field.
- A portfolio of experiments of different cost and time scales is an integral part of our physics program. Such experiments include:
  - experiments measuring electric dipole moments, in particular the proton EDM measurement in a storage ring, along with experiments exploiting synergies with AMO techniques to examine fundamental symmetries;
  - experiments probing rare light meson decays, such as JEF [2,3] and REDTOP [4];
  - involvement of the US experimental community in the vibrant international program at both CERN and J-PARC studying rare K decays;

  - the PIONEER experiment at PSI will study lepton universality in the muon and electron generations, and is a promising medium-scale experiment that should be supported.

- We also stress that small and medium-sized multipurpose experiments allow early career researchers to gain experience in many stages of an experiment, from proposal writing to design and construction to publication. Examples are the Fermilab $g-2$ or the quark flavor experiments, which allow junior scientists to participate in instrument construction or computationally intensive tasks, as well as develop significant physics analysis expertise. In addition, the relatively small sizes of these experiments allow for less hierarchical organization, with a broad array of leadership opportunities. A commitment to mentor early career scientists in a supportive and inclusive environment is guiding our programmatic choices.

Physics of the Frontier and the P5 Drivers

The Rare and Precision Frontier covers a broad range of topics, defined by neither a particle nor a machine. It is broadly aligned with the Intensity Frontier in the 2013 Community Summer Study [5], except for the removal of the physics of neutrinos, which now is the focus of a separate Frontier. During the last P5 cycle, many of the various physics topics encompassed by our Frontier fell into the general "Explore the unknown: new particles, interactions, and physics principles" driver [6]: this broad motivation, which is the strong connecting theme of all of the efforts current and planned in the particle physics community, is correctly identified as taking two basic forms: producing new particles and detecting the quantum influence of new particles. Many experimental efforts discussed below fall into the latter category. Before we summarize how the RPF program contributes to the physics drivers identified in previous community studies, we will articulate the need for a new physics driver centered around the physics of flavor. This driver puts many theoretical and experimental advances over the last decade in proper focus and defines clearer objectives for the future.

A new physics driver: flavor physics as a tool for discovery

"Flavor physics" is defined as physics that distinguishes the generations. We see three generations of quarks, and three generations of leptons. This replication, combined with the unexplained pattern of masses of quarks and leptons, which spans several orders of magnitude, is a central mystery of particle physics. Both quarks and leptons exhibit inter-generational mixing, with different patterns for the quarks (the CKM matrix) and the neutral leptons, or neutrinos (the PMNS matrix.) The reason for this difference is still unknown, but we must answer these questions in order to form a coherent picture of the elementary particles and their interactions. In addition, the richness of decays of different flavor species available to experimental observation allows us to probe deviations from SM expectations with a multitude of approaches that we will summarize below. Here the increasing precision of many ongoing and proposed experiments already shows some intriguing anomalies and may provide further clues to the nature and scale of the new physics.

Much of our Frontier centers on these two themes. Weak decays of all the quarks and the CKM matrix are subtle probes of deviations of Standard Model expectations and already constrain reasonably well the number of generations — precision measurements of the CKM triangle and tests of unitarity are at the core of the Frontier. Rare decays seek to uncover new physics manifesting itself through interference with Standard Model diagrams. Searches for charged lepton flavor violation examine the nature of lepton flavor and, through $\Delta L = 2$ processes, extend our flavor studies to the sources of leptogenesis. Whether in the B, D or K systems, comparisons of decay rates into different lepton species challenge the notion of lepton

universality, strongly implied by the Standard Model. Hence flavor studies are either at the core or crucial tools across our Frontier, and the nature of flavor is a basic question in particle physics.

Relation to 2014 P5 Drivers

We next turn to the connections between the different physics topics of the Frontier and the P5 drivers identified after the 2013 community summer study. First, we aim at spelling out these relations. Second, we show how the Frontier is related to the other Frontiers. Third, we show how a full understanding of the puzzles motivating particle physics require the study of both flavor-dependent and flavor-independent phenomena. As a reminder, the 2014 P5 Drivers were:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

We have relatively little direct connection to cosmic acceleration and focus on the other drivers.

Use the Higgs boson as a new tool for discovery

The Rare and Precision Frontier's purview includes using precise measurements to search for deviations from the Standard Model. Intellectually, precision Higgs physics is part of the Rare and Precision Frontier. Functionally, such measurements have been assigned to the Energy Frontier because Higgs factories, such as the proposed FCC-ee, are colliders, and colliders are assigned to the Energy Frontier.

Since much of physics objective of the Rare and Precision Frontier relies on indirect measurements, we provide examples of how RPF measurements depend on Higgs properties. In the interest of length, we only mention a few highlights and refer the reader to the Topical Group reports for a more in-depth discussion [7–9].

Lepton universality tests which could be related to the Higgs properties abound in b and c decays because of the dependence on the Higgs coupling on mass. A charged Higgs would couple much more strongly to the τ than the muon or electron. Ratios of $b \to c\tau\overline{\nu}_\tau$ to $b \to c\ell^-\overline{\nu}_l$, usually called $R(X_c)$, where X_c is the charmed hadron in the final state, are a natural place to search. The world averages of results for $R(D)$ and $R(D^*)$ exceed the Standard Model prediction with a combined significance of $\sim 3\sigma$, pointing to possible violations of lepton flavor universality [7]. A composite Higgs could be responsible for the violation of flavor universality possibly seen in $B^+ \to K^+\ell^+\ell^-$ [10].

Lepton-flavor violating Higgs decays have been the subject of considerable attention [9]. Searches for LFV decays of the Higgs have been performed by the ATLAS, CMS, and LHCb experiments. In addition, searches for Higgs decays into $e\tau$ or $\mu\tau$ pairs have been performed for different τ decays channels (and the FCC-ee could perform similar searches for Z decays.) Triplet Higgs models can predict lepton flavor violation, especially in $\mu \to 3e$ [11].

Pursue the physics associated with neutrino mass

The RPF topical group focused on baryon and lepton number violation shares an interest on $0\nu2\beta$ decays with the Neutrino Frontier. The question of whether neutrino is its own antiparticle has important implications for the matter-antimatter asymmetry of the Universe, as many scenarios of leptogenesis require neutrinos to be Majorana particles.

The physics associated with neutrino mass should certainly include the understanding of the PMNS matrix. The driver does not explicitly mention the structure of this matrix, but the reasons for neutrino flavor mixing and the non-diagonal nature of the matrix, in contrast to the relatively diagonal CKM matrix, indicate the physics of neutrino flavor differs in unexplained ways from the physics of quark flavor. In addition, some scenarios of leptogenesis require CP-phases of the PMNS matrix for the explanation of the observed matter-antimatter asymmetry.

Identify the new physics of dark matter

The RPF has a vibrant community focused on a new set of intensity-frontier experiments that will offer crucial insights into the physics of dark sectors, highlighted as a *Priority Research Direction* in the 2018 "Dark Matter New Initiatives" study [12]. The types of dark matter examined in the Frontier are roughly in the range between the electron and proton mass with couplings to the SM consistent with what was needed for thermal production in the early Universe. Accelerator-based dark-sector experiments include multipurpose detectors at colliders and flavor factories, along with dedicated fixed-target experiments and downstream detectors [13, 14].

Explore the unknown: new particles, interactions, and physical principles

Every physics Frontier explores the unknown and searches for new phenomena. Nevertheless, the RPF makes unique contributions. For example, we have already discussed the physics of flavor as a unique focus of the RPF: studies of the CKM matrix, charged lepton flavor violation, and much of the physics of weak decays belong to the RPF. Some studies have synergies with other frontiers. Other inquiries, such as tests of fundamental symmetries in small experiments, are unique to the RPF. The RPF studies:

- electric dipole moments and new sources of CP violation ranging from fundamental particles to molecules and using both small-scale AMO methods as well as storage rings;
- rare decay modes of charm and beauty hadrons [15], as well as rare kaon decays, such as $K_L \to \pi\ell\ell$ or $K \to \pi\nu\overline{\nu}$, which are exceptionally stringent tests of the Standard Model;
- magnetic dipole moments of the electron, muon and tau leptons;
- flavor universality, in beauty and charm decays, in τ decays, and in precision tests using π and K decays;
- violations of Lorentz symmetries and precision tests of gravity.

These signature searches, combined with the physics of flavor, expand the RPF far beyond the "Intensity Frontier." The breadth of tools for new physics searches perhaps single out the RPF as the Frontier most directly related to the exploration of the unknown.

9.1 Introduction

Particle physics tries to understand the innermost structure of the Universe and the dynamics underlying its origin and evolution. Enormous strides have been made in the last few decades, with a solid body of work confirming the beauty and power of the theory that we call the Standard Model, which is able to describe and predict countless observations, in some cases with impressive accuracy. Yet we strive for a deeper knowledge, motivated by puzzles that still await a more complete explanation. The physics topics we grappled with in our Frontier are closely intertwined with some of these profound questions. For example, the stability of the Universe we live in is rooted on the asymmetry between matter and antimatter abundances. Sakharov identified three conditions necessary for this occurrence [16]: baryon number violation, new sources of C and CP violation, and interactions out of thermal equilibrium. Several of the studies that we consider have unique sensitivities to new sources of CP violation and baryon number violation. Another important example is the elusive nature of dark matter, which is more abundant than ordinary matter and whose nature remains unknown: its only well-measured property is its gravitational interaction with ordinary matter. The study of a possible dark sector interacting with ordinary matter via portals can shed light on some plausible dark matter candidates.

While we have compelling reasons to expect that new particles and interactions are needed to achieve a more complete picture of the microworld, the mass scale of this new physics is not known. It is possible that it is light and very weakly interacting, or it is possible that it is much higher than the $\approx$ TeV scale originally anticipated. Precision measurements, probing quantum effects that allow heavy new particles to manifest themselves through their effects on rare and forbidden decays in the SM paradigm, exploit large data sets and precise instruments to probe mass ranges beyond the direct reach of high-energy machines. Fig. 9-1 illustrates the mass scale reach of some of the measurements discussed in this report, and much useful discussion can be found in Ref. [17].

The report is organized as follows. First, Section 9.2 describes how the RPF study was organized into seven areas considered by corresponding working groups. Next, in Section 9.3, we discuss the current experimental status of the broad suite of rare processes and precision measurements examined in our study, and the ways in which future improvements may be achieved in the medium- and long-term future, with upgrades to existing facilities and experiments or new initiatives. Section 9.4 summarized the R&D efforts needed to support this experimental program. Section 9.5 covers the theoretical landscape, and how different theoretical approaches can illuminate or guide experimental studies. Section 9.6 elucidates the connections with other frontiers and experimental programs, and we review the impact of our work on education and society. Finally, we conclude with the big ideas emerging from this study.

9.2 Major themes of the RPF topical groups

The broad physics landscape examined by the RPF is organized into seven topical groups, who articulated its fundamental components. Here we summarize the main themes explored in each topical group.

9.2.1 Weak decays of b and c quarks

Studies of heavy-flavored hadrons provide rich, diverse, and model-independent probes for new physics at energy scales far beyond what is directly accessible. Heavy-flavor physics is crucial to our search for new

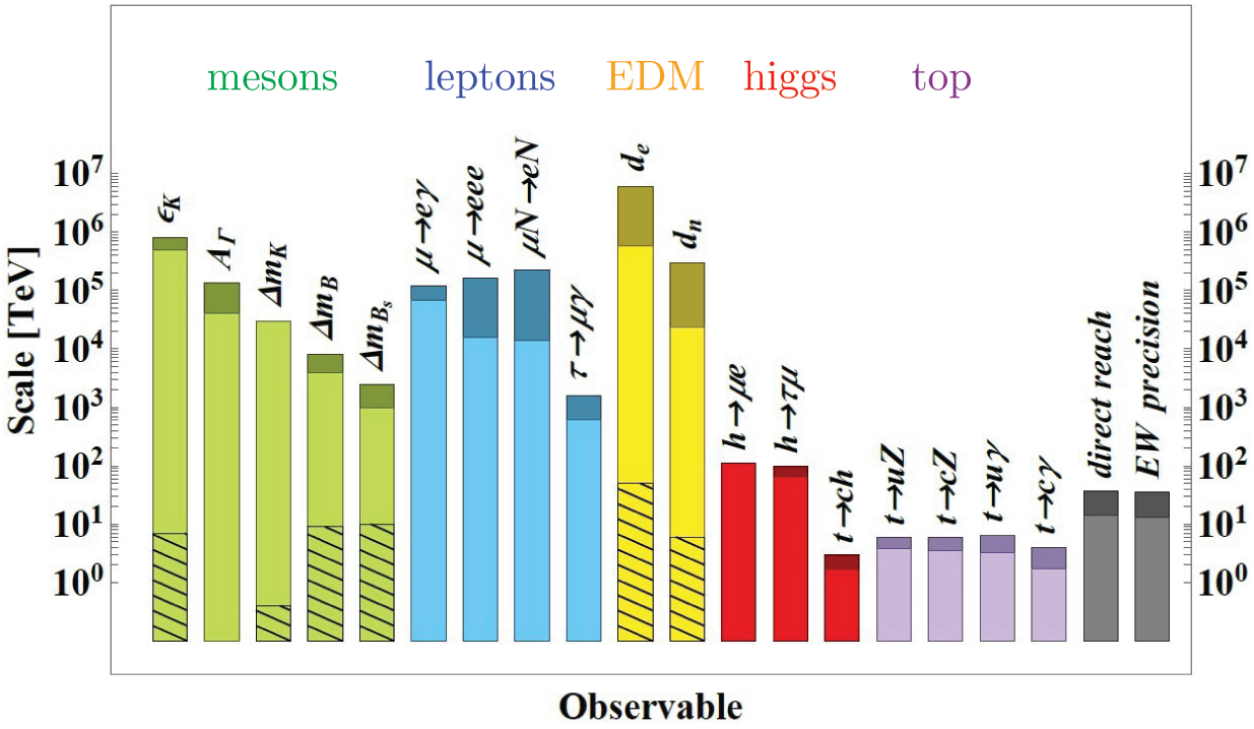

Figure 9-1. *Reach in new physics of present and future facilities, from generic dimension-six operators. Different probes are identified by color coding: green is for mesons, blue for leptons, yellow for EDMs, red for Higgs flavored coupling, and purple for the top quark. The grey columns illustrate the reach of direct searches and electroweak precision studies. The coupling coefficients of these operators are taken to be of* $\mathcal{O}(1)$ *in the solid color columns or suppressed by MFV factors (hatch-filled surfaces). Light colors correspond to present data, and dark colors correspond to mid-term prospects in the time scale of the HL-LHC [17, 18].*

physics in the upcoming 10–20 years, important advances are expected through a highly synergistic program of experiments: LHCb and its planned upgrades at the LHC, Belle II at the SuperKEKB asymmetric e^+e^- collider, and the e^+e^- charm factories BESIII and STCF. In particular, Belle II and LHCb have the unique potential to unveil new physics by confirming intriguing hints of deviations from the Standard Model that have been recently observed in $b \to s\ell^+\ell^-$ and $b \to c\tau\overline{\nu}$ transitions at BaBar, Belle, and LHCb, or finding new unexpected outcomes in the study of rare and forbidden decays such as $b \to s\nu\overline{\nu}$ or $B_{(s)} \to \ell^+\ell^-$. In addition, the continuing refinement of the studies of quark mixing, flavor oscillations and CP violation may unveil subtle deviations from SM expectations. Farther into the future, the experimental program can be extended at the e^+e^- circular colliders proposed for precision studies of the Higgs boson. The U.S. flavor community is well-positioned to lead key aspects of the physics, computing, and detector construction in all of these experimental programs. Theoretical efforts that inspire and elucidate the fundamental impact of experimental findings are crucial to success and should be supported. The lepton universality and other stringent tests foreseen in these experiments and their upgrades are discussed in the b and c topical group report [7].

9.2.2 Weak decays of the light quarks

Studies of the light quarks include precision measurements of both flavor-conserving and flavor-violating decays of kaons, hyperons, and η/η' mesons. Tests of new physics through checks of the unitarity of the first column of the CKM matrix, along with lepton flavor/number and lepton universality tests, have revealed experimental anomalies. These findings require additional experimental and theoretical studies of the light quark systems to conclusively assess their impact. Synergy with the studies of the heavy quark systems is assured.

The study of K physics is centered in Europe and Asia, but a small and vibrant community in the US is contributing to this important program. Such experiments are natural complements to searches of new physics in b-decays and provide constraints to the CKM unitarity triangle. New ideas exploit rare pion decays, such as PIONEER, which plans to study the ratio $R_{e/\mu} = \Gamma(\pi^+ \to e^+\nu_e)/\Gamma(\pi^+ \to \mu^+\nu_\mu)$ to 0.01% precision, probing up to PeV mass scales [19]. In later stages, the experiment could study pion beta decay ($\pi^+ \to \pi^0 e^+(\gamma)$), testing CKM universality through the precision measurement of $|V_{ud}|$. Finally, η decays experiment JEF [2, 3], and the η/η' factory REDTOP (which has been proposed as a part of the U.S. particle physics program [4]) study fundamental symmetries in these systems and contribute to dark sector studies.

9.2.3 Fundamental Physics in Small Experiments

The study of static properties of elementary particles (electric and magnetic moments) and the fundamental symmetries (C, P, T, and their combinations, along with basic tests of Lorentz symmetry), all probe energies all through the Planck scale. The experiments addressing this physics are of small to intermediate size and sometimes involve methods not traditionally considered high-energy physics. Nonetheless, in subjects such as $n\overline{n}$ oscillations, EDMs, and $0\nu2\beta$, the intellectual techniques, methods, and people frequently overlap, and artificial divisions impede progress. We worked to identify ways to develop a synergistic physics program that exploits the expertise of scientists working in the high-energy physics community, the relevant AMO and nuclear physics to promote collaborative efforts that will make this research flourish.

Storage ring EDM experiments are an exciting opportunity. Proton storage ring experiments might reach $10^{-29} e \cdot cm$ in a decade, with deuterons achieving similar levels between five and ten years later [20, 21]. Like the FNAL $g-2$ experiment, the technique calls for running at a "magic momentum" (0.7 GeV/c for the proton). The proponents have developed plans for a Brookhaven National Laboratory (BNL)-sited experiment, but the experiment could be sited elsewhere.

Low-energy antimatter gravity tests and fifth force tests using muonium could be performed at the Advanced Muon Facility (AMF) facility described in Section 9.2.5. These experiments are also synergistic with possible efforts for precision measurements of the muonium spectrum and searches for muonium-antimuonium oscillation. Studies for a low-energy muon facility are underway [22].

9.2.4 Baryon and Lepton Number Violation

The evolution of the Universe from its matter-antimatter symmetric state just after the Big Bang to its current asymmetric state requires the presence of one or both of baryon (B) or lepton (L) number-violating interactions. The Standard Model cannot produce the observed baryon-antibaryon asymmetry: the Higgs mass is too large to ensure that the electroweak phase transition is sufficiently first order and the size of CP-violation is too small.

We can search for new sources of baryogenesis in a set of experiments looking for possible baryon number violating processes, such as B-violating baryon decays and baryon-antibaryon oscillations. These searches are linked to the nature of neutrinos: if neutrinos are Majorana particles and violate CP, there are well-motivated scenarios of leptogenesis that could explain the observed baryon asymmetry [23].

Experimental and theoretical research in B/L-number violation (such as proton decay, $n - \overline{n}$ oscillations, and searches for $0\nu2\beta$ decays) is traditionally supported by nuclear physics. These efforts share many of the same intellectual problems, methods, and people with HEP. Unfortunately, this separation produces barriers that make it difficult for researchers at the intersection between these communities.

Studies of neutrons are another avenue of opportunity for profound discoveries. One particular opportunity of note is the study of $n\overline{n}$ oscillations. The proposed NNBar experiment at the ESS could reach a limit of $\tau_{n\overline{n}} \sim 10^{9-10}$ s [24–26]. "Mirror neutrons," $n \to n'$ oscillations, have been ruled out as an explanation of the discrepancy between neutron lifetimes measured with cold and ultracold neutrons, but improved sensitivity to this phenomenon is possible at the HIBEAM program at the ESS [25].

9.2.5 Charged Lepton Flavor Violation

Charged lepton flavor violating/violation (CLFV) processes are interactions that do not conserve lepton family number. Neutrinos change their flavor through oscillations, expressed in the PMNS matrix; quarks change theirs through the weak interaction and the CKM matrix. The archetypal CLFV decay is $\mu \to e\gamma$ (with no emitted neutrinos), compared to the normal weak decay of $\mu \to e\nu_\mu\overline{\nu}_e$. We have never observed CLFV transitions among muons, electrons, and taus. A fundamental question that arises from current observation is why mixing occurs in quarks, whereas in the lepton sector, mixing occurs only among neutrino species.

Muons play a unique role in CLFV searches because we can make intense beams of muons and achieve the highest statistical sensitivity. Therefore it is important to explore initiatives that can push our sensitivity

even further. In muon-to-electron conversion, $\mu^- N \to e^- N$, the Mu2e experiment at Fermilab will reach its goal of $R_{\mu e} = \Gamma(\mu^- N \to e^- N)/\Gamma(\mu^- N \to \text{all muon captures}) < 8 \times 10^{-17}$ at 90% CL by the end of the decade. A factor of ten upgrade from Mu2e, Mu2e-II, needs R&D effort to both improve the limit and change the physics probed with a different target nucleus N, most likely Ti [27]. PIP-II at Fermilab could not only provide profound improvements in this channel but also open intriguing possibilities for a comprehensive muon CLFV program. The proposed AMF facility exploits the PIP-II beam and a pair of new rings. It could improve limits on muon-to-electron conversion, $\mu^- N \to e^- N$, by at least one order of magnitude beyond Mu2e-II, and it would also enable the study the physics underlying a signal by varying the Z of the nucleus N. Using high-Z materials such as Au is impossible without PIP-II and the new rings. Furthermore, the facility would allow us to examine the two muon rare decay modes $\mu \to e\gamma$ and $\mu \to 3e$ at rates far beyond those achievable at any other planned facility; here detector R&D is essential to use the rates available at PIP-II. AMF would also enable a dark matter experiment [28]. This program requires rebunching the PIP-II beam and a fixed-field alternating gradient synchrotron (FFA) [29]. A proposal for such a facility requires significant R&D, and the R&D required for targeting in a solenoid is closely related to that needed for the muon collider [9].

Charged lepton flavor violating τ decays are complementary to analogous μ decays, and they can be pursued in heavy-flavor experiments such as Belle II, LHCb, or a prospective tau-charm factory. GIM suppressions are smaller in the τ sector; thus we can set stringent limits for τ-based CLFV with much smaller samples and limits of the order of 10^{-9} to 10^{-10} are expected at the upcoming e^+e^- experiments. CLFV in Higgs decays can be studied at colliders by searching for $H \to \tau\mu$ and $\to \tau e$ [30].

9.2.6 Dark Sector at High Intensity

The possibility of a dark sector neutral under Standard Model forces furnishes an attractive explanation for the existence of Dark Matter. Dark sectors are a compelling new physics direction to explore in its own right, with potential relevance to fundamental questions as varied as neutrino masses, the hierarchy problem, and the Universe's matter-antimatter asymmetry. Because dark sectors are generically weakly coupled to ordinary matter, and because they can naturally have MeV-to-GeV masses and respect the Standard Model's symmetries, they are only mildly constrained by high-energy collider data and precision atomic measurements. Intensity Frontier experiments offer unique and unprecedented access to experimental studies of the dark sector with possible access to specific dark matter candidates [14].

The continued exploitation of already existing large multipurpose detectors, especially Belle II and LHCb, to study dark-sector states is a crucial aspect of this physics program. In addition, dedicated efforts at high-intensity accelerators have started. The Dark Matter New Initiative (DMNI) report has given initial support to two experiments, and a promising set of experiments has been identified since the last P5 report [12]. A broader, coordinated program is emerging from this initial work. Dark-sector theory will also be critical. Advances in theory will both address open problems in particle physics and cosmology, and maximize the efficacy of the experimental program, where the track record of theorists pioneering new approaches is strong. A core consensus in the Frontier is that the U.S. should identify and pursue a well-planned portfolio of these experiments.

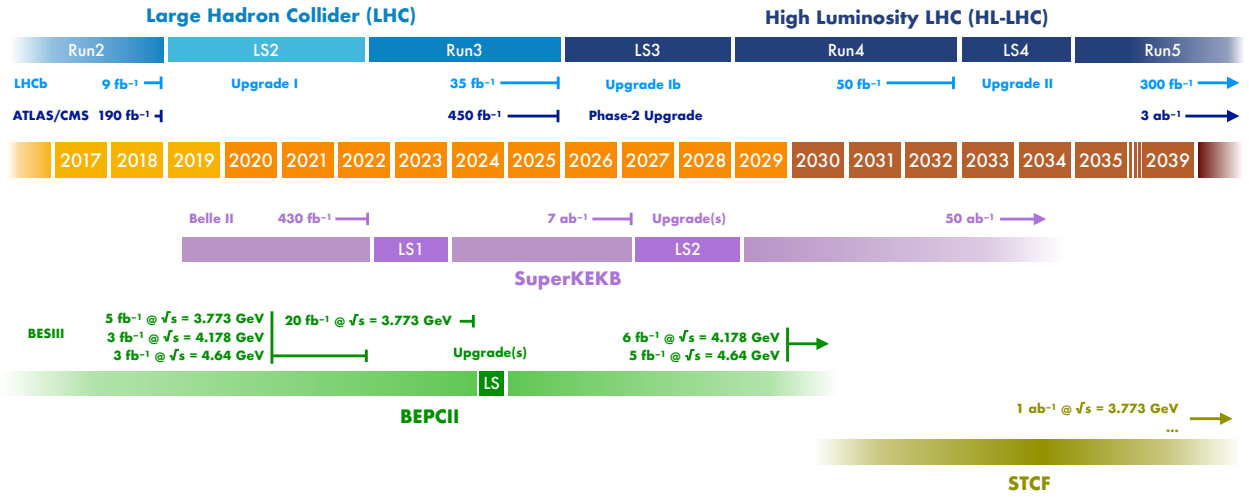

Figure 9-2. *Timeline for the proposed experimental program in heavy flavor physics.*

9.2.7 Hadron Spectroscopy

Hadron spectroscopy encompasses the experimental investigation of the pattern of hadron masses and quantum numbers and the elucidation of their nature with non-perturbative QCD calculations. New states discovered by LHCb, Belle/Belle II, BESIII, and other experiments do not always fit among conventional hadronic states. New exotic states, such as tetra- and pentaquarks, hybrids, etc., are added every year. A key question arising from the multitude of newly discovered states is whether they can fit in a unified description of multiplets with a similar underlying structure. Configurations such as hadron molecules, compact multiquark states, or even linear combinations of such components, are possible and require careful experimental measurements to disentangle [31].

9.3 Experimental Methods

The physics drivers described above need a variety of experimental approaches, featuring different beams and detector designs, as well as different scales of investment and duration, to come to fruition. Some of the experiments considered have a solid data-taking record and are envisaging staged upgrades in different phases of development. Others are about to take data and are considering significant updates. Finally, new concepts are proposed and are currently in an early but promising stage.

We begin our survey with high-precision heavy-flavor experiments; such experiments are essential to our physics program. Their timeline is summarized in Fig. 9-2.

Two of them encompass a vast program of measurements that use beauty and charm decays as tools for discovery: LHCb, the first experiment optimized to pursue heavy flavor decays at the LHC, and Belle II, operating at the SuperKEKB accelerator. They are both state-of-the-art detectors, featuring excellent tracking, particle identification, and high-acceptance electromagnetic calorimeters. LHCb operates at the LHC, exploiting the higher b-production cross section and higher boost that allows superb vertex resolution and proper time resolution of the order of 40 fs. In addition, a great variety of b and c hadron species are accessible. Belle II exploits the simplicity of the e^+e^- initial state to implement kinematic constraints that

are effective in the study of inclusive properties of the lighter B mesons, as well as quantum coherence of the initial $B\overline{B}$ state.

The LHCb experiment collected 9 fb^{-1} of pp collisions during Run I and Run II of the LHC and is now commissioning its first major upgrade during the early data-taking phase of Run III. The first data set has already demonstrated the impressive range of measurements within LHCb reach, from the discovery of CP violation in the charm sector [32] and in the B_s^0 system, major inputs to the study of lepton flavor universality, and the first complete analysis of the angular observables in $b \to s\ell^+\ell^-$. LHCb is already making strides in measurements of rare K decays and is planning to pursue rare hyperon decays as well. Heavy baryon-antibaryon oscillations [33] may provide clues to baryogenesis [34]. The field of hadron spectroscopy is already blossoming, with the observation of nearly sixty exotic hadronic states of matter, including pentaquarks [35]. In addition, LHCb has already put in place a program of measurements that provide complementary information to the big general-purpose experiments (ATLAS and CMS) in the study of key electroweak parameters, such as the W boson mass, as well as searches for heavy Majorana neutrinos and W lepton flavor-violating decays [36–38]. The most innovative feature of the LHCb upgrade I, currently being commissioned, is the implementation of a software trigger that processes data in real time [39], rather than a simple first-level filtering scheme based on hardware thresholds. This strategy [40] allows the experiment to adjust the triggering algorithm to the evolving knowledge of these decays and to augment its efficiency for hadronic channels. This feature, combined with an increase in the maximum instantaneous luminosity the experiment can process, allows significant improvement in the measurement of key quantities. The goal of LHCb upgrade I is to collect 50 fb^{-1}. A subsequent major update is planned for installation in the time frame of CERN LS4 ($\approx$ 2031) and is currently incorporated in the LHC planning [41]. The goal is to maintain or improve the detector performance while taking data at an instantaneous luminosity of 1.5×10^{34}cm^{-2}s^{-1} and accumulate a data sample of 300 fb^{-1} during HL-LHC operation. This requires operation at a much higher pile-up rate ($\sim$ 40 interactions per crossing). Thus a redesign of major detector components is needed, with special consideration given to the inclusion of precise timing (a few tens of ps) in the detector and associated electronics design. This feature makes possible the association of tracks and showers to specific primary vertices and significantly aids in pattern recognition.

The Belle II experiment has been taking data at the asymmetric SuperKEKB e^+e^- collider since 2019 and has collected $\sim$ 430 fb^{-1} in the data-taking period ending with the Long Shutdown I of Summer 2022, roughly corresponding the sample collected by BaBar. While the current data-taking does not represent a significant increase in the statistical accuracy of the Belle data set, novel techniques to improve the experiment's sensitivity have been implemented, with promising results illustrated by the $B \to K\nu\overline{\nu}$ mode [42]. The experiment aims to collect 50 ab^{-1} by the mid-2030s. [43]. To achieve this goal, SuperKEKB needs to reach a peak luminosity of 6.5×10^{35} cm^{-2}s^{-1} through upgrades planned for the Long Shutdown 2, currently scheduled for 2027–2028 [44]. An international task force has been formed to advise to SuperKEKB on the possible upgrade options, including a redesign of the interaction region and the final focus system. Long Shutdown 2 allows upgrading subsystems of the Belle II detector as well. In addition, a possible upgrade of the SuperKEKB machine to feature beam polarization would allow precision electroweak and precision τ physics measurements [7].

A similar experimental approach is used by the BES III experiment at BEPCII and may be further explored at the proposed super tau-charm (STCF) factory in China. In addition, the two general purpose experiments at the LHC, ATLAS, and CMS, have a heavy flavor program competitive in final states including muons and in spectroscopy studies. In the longer term, the FCC-ee program can build upon the strength of colliders to pursue flavor physics opportunities relevant to the time scale of operation.

Table 9-1 summarizes the evolution of the precision achievable for important measurement as different upgrades are implemented and larger samples are accumulated. As the statistical accuracy improves with higher luminosity, the control of systematic effects and theoretical uncertainties becomes increasingly

important. The complementarity in experimental approaches between e^+e^- high luminosity collider experiments and experiments taking data at hadron machines is essential to the success of this physics program. LHCb and Belle II provide complementary information on key observables in B^0 and B^+ decays, as well as in hadron spectroscopy, searches for charged lepton flavor violation in τ decays and charged lepton flavor violation in b-hadron decays, and in the exploration of the dark sector. Belle II has an easier path to inclusive measurements and exploits the simplicity of the initial state. LHCb and its upgrades have a higher production cross section and a richer array of b-flavored hadrons to study. Fundamental tests such as lepton universality violation or precision determinations of the CKM parameters $|V_{ub}|$ and $|V_{cb}|$ are prime examples of such a synergy, where a diverse array of methods and measurements may help in pinning down long-overdue unresolved tensions. Lastly we point out that study of rare and forbidden τ decays, accessible in these experiments, is complementary to the several dedicated experiments searching for rare μ decays described below [45].

Observable	Current best	Belle II 50 ab^{-1}	Belle II 250 ab^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	ATLAS 3 ab^{-1}	CMS 3 ab^{-1}	BESIII 20 fb^{-1} (∗)	STCF 1 ab^{-1} (∗)
Lepton-flavor-universality tests									
$R_K(1 < q^2 < 6\ \text{GeV}^2)$	0.044 [46]	0.036	0.016	0.017	0.007				
$R_{K^*}(1 < q^2 < 6\ \text{GeV}^2)$	0.12 [47]	0.032	0.014	0.022	0.009				
$R(D)$	0.037 [48]	0.008	< 0.003	na	na				
$R(D^*)$	0.018 [48]	0.0045	< 0.003	0.005	0.002				
Rare decays									
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ [10^{-9}]	0.46 [49,50]			na	0.16	0.46–0.55	0.39		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.69 [49,50]			0.27	0.11	na	0.21		
$\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-)$ UL [10^{-3}]	2.0 [51,52]	0.5	na						
$\mathcal{B}/\mathcal{B}_{\text{SM}}(B^+ \to K^+\nu\overline{\nu})$	1.4 [53,54]	0.08–0.11	na						
$\mathcal{B}(B \to X_s\gamma)$	10% [55,56]	2–4%	na						
CKM tests and CP violation									
α	5° [57]	0.6°	0.3°						
$\sin 2\beta(B^0 \to J/\psi K_s^0)$	0.029 [58]	0.005	0.002	0.006	0.003				
γ	4° [59]	1.5°	0.8°	1°	0.35°			0.4° (†)	$< 0.1°$ (†)
$\phi_s(B_s^0 \to J/\psi\phi)$	32 mRad [60]			10 mRad	4 mRad	4–9 mRad	5–6 mRad		
$\lvert V_{ub}\rvert(B^0 \to \pi^-\ell^+\nu)$	5% [61,62]	2%	$< 1\%$	na	na				
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert(\Lambda_b^0 \to p\mu^-\overline{\nu})$	6% [63]			2%	1%				
$f_{D^+}\lvert V_{cd}\rvert(D^+ \to \mu^+\nu)$	2.6% [64]	1.4%	na					1.0%	0.15%
$S_{CP}(B^0 \to \eta' K_s^0)$	0.08 [65,66]	0.015	0.007	na	na				
$A_{CP}(B^0 \to K_s^0\pi^0)$	0.15 [65,67]	0.025	0.018	na	na				
$A^{CP}(D^+ \to \pi^+\pi^0)$	11×10^{-3} [68]	1.7×10^{-3}	na	na	na			na	na
$\Delta x(D^0 \to K_s^0\pi^+\pi^-)$	18×10^{-5} [69]	na	na	4.1×10^{-5}	1.6×10^{-5}				
$A_\Gamma(D^0 \to K^+K^-, \pi^+\pi^-)$	11×10^{-5} [70]	na	na	3.2×10^{-5}	1.2×10^{-5}				

Table 9-1. *Projected uncertainties (or 90% CL upper limits) in several key heavy-flavor observables over the next two decades. A missing entry means that the observable cannot be measured; the abbreviation* na *means that, although the observable can be measured, the projected uncertainty is not available. Projections are taken from Refs. [43, 44, 71] (Belle II), Refs. [41, 72] (LHCb), Ref. [73] (ATLAS and CMS), Refs. [74, 75] (BESIII and STCF).* (∗) *Integrated luminosity at* $\sqrt{s} = 3.773$. (†) *Projected uncertainties on* γ *resulting from BESIII/STCF measurements of the D strong-phase differences, which will contribute as external inputs to the Belle II and LHCb measurements.*

The experimental study of kaon decays has played a crucial role in flavor physics as a tool for discovery, and exciting prospects are on the horizon. The ultra-rare $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ decays with SM branching ratios of $\mathcal{O}(10^{-11})$ are theoretically well-understood and complement the experiments in the B sector [76] in the exploration of indirect evidences for new physics. A vibrant experimental program aiming primarily at the measurement of these decays is currently ongoing in Europe (NA62) and Japan (KOTO); the NA62 experiment has recently reported evidence of the $K^+ \to \pi^+\nu\overline{\nu}$ decay with a 3.4σ significance [77]. Beyond the flagship modes, the two experiments pursue a broad program of rare kaon decay measurements [78], tests of SM symmetries and CKM unitarity, and searches for hidden sectors [79], in a complementary way to other flavor experiments. The challenges of kaon experiments lie in the operation at GHz beam rates required for the collection of samples of $\mathcal{O}(10^{13})$ decays, precision timing (to sub-100 ps resolution), and background suppression. Both the NA62 and KOTO experiments are implementing significant upgrades and envisage long-term programs [80].

An experiment to probe lepton universality violation in $\mathrm{BR}(\pi \to e\nu)/\mathrm{BR}(\pi \to \mu\nu)$ and the rare pion beta decay $\pi^+ \to \pi^0 e^+ \nu_e(\gamma)$ decay has been recently approved at the Paul Scherrer Institute [81]. The experiment is currently in the R&D phase, where technological options that allow optimum separation between signals and potential backgrounds are being considered. The targeted measurements are connected to recently reported anomalies [81]. The technologies being explored are active, segmented targets using AC coupled low gain avalanche detectors (AC-LGADs) to implement a 4-dimensional hit reconstruction, surrounded by a fast, deep, and high-resolution calorimeter [82]. Potential technologies are a LXe calorimeter or a hybrid LYSO + CsI crystal combination. In addition, state-of-the-art trigger and data-acquisition systems must be implemented.

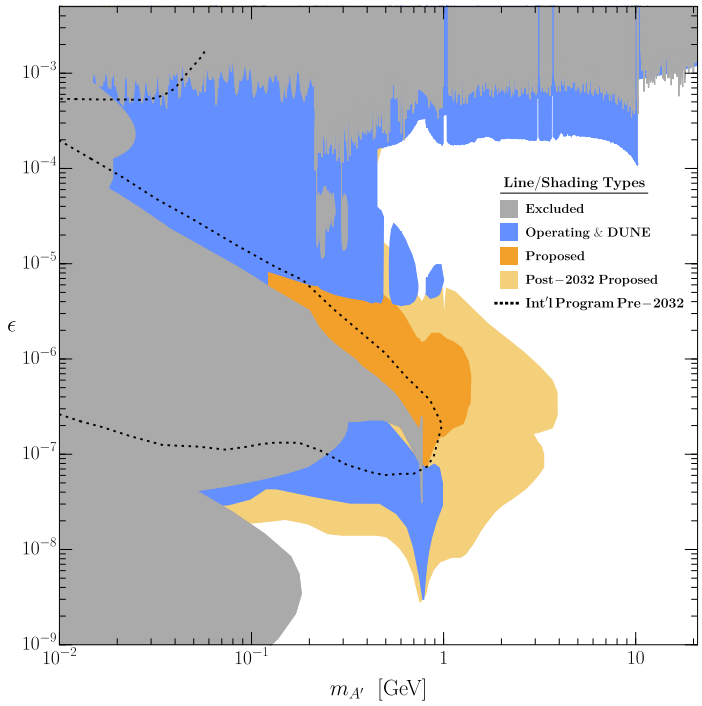

Figure 9-3. *Prospects on near-term sensitivities and future opportunities to search for visibly decaying dark photons interacting through the vector portal. Exclusion limits are shown in terms of the dark photon mass ($m_{A'}$) and kinetic mixing (ϵ) parameters [87]. This parameter space is compatible with secluded heavier thermal dark matter [88]. Constraints from past experiments (gray regions) and projected sensitivities from operating and fully funded experiments and DUNE (blue regions), and other proposed near-term (pre-2032) experiments both based in the U.S. or with strong U.S. leadership (orange region) are shown. Primarily international projects are shown as a dashed line, and proposed experiments farther into the future are displayed in light yellow. This plot is for only one portal; similar curves for other cases are given in the subgroup report. Figure and caption adapted from [13].*

Another approach to exploit large samples of light mesons as a tool for discovery is the use of large samples of η and η' mesons, as in the upcoming JEF experiment [2, 3] and the proposed REDTOP experiment [4]. Their main goals are to search for the violation of fundamental symmetries or lepton flavor universality, and possibly to study rare decays of these mesons as a probe of particles that act as portals to a possible dark sector. The proposed REDTOP detector is a 4π detector surrounding a Li target. The expected rate is 1 GHz of inelastic collisions, with $5.1{\times}10^6$ η's produced. The η and η' mesons are produced almost at rest;

the minimization of the material budget in the detector is thus a primary consideration. In addition, the experiment has to cope with an inelastic event rate of $\approx 7 \times 10^8$ Hz; thus the trigger and data processing pose significant challenges. Although several detector choices and the facility hosting the experiment still have to be finalized, the experiment aims to take data starting within the next decade.

A broad program of dark sector studies at intensity machines is a pillar of our proposed research program. The nature of dark matter remains elusive, and the "WIMP miracle" did not materialize as predicted. A well-motivated possibility is that the dark matter is composed of particles that are part of a dark sector similar in structure and perhaps complexity to the SM. Dark matter particles might interact with other dark matter particles via dark forces mediated by new gauge bosons and with ordinary matter through the exchange of dark forces. These new forces may have structures similar to the known forces [83]. For example, dark matter particles could interact via a dark force similar to the electromagnetic force felt by ordinary matter. The dark photon A' that mediates this force can have a weak coupling to the standard electromagnetic current through the kinetic term $\epsilon F^{\mu\nu} F'_{\mu\nu}/2$, where ϵ characterizes the strength of the mixing. Figure 9-3 illustrates the parameter space that could be probed in the near and intermediate time scales.

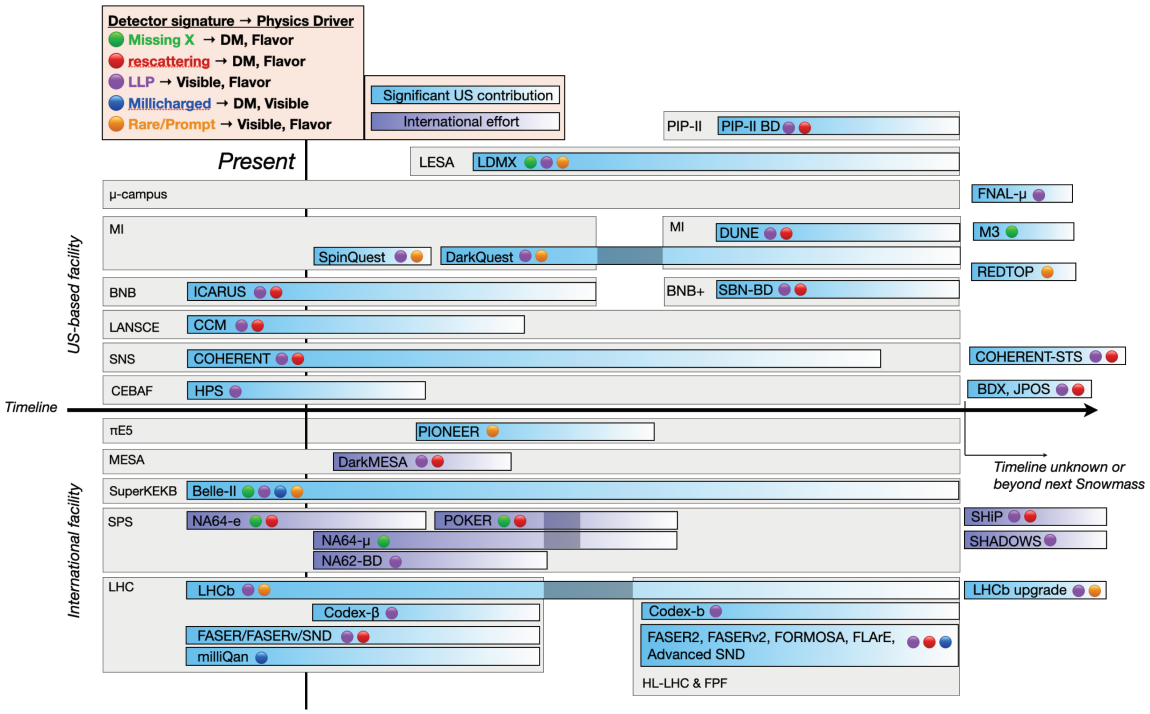

Figure 9-4. *Timeline for the proposed experimental program to study the dark sector at high-intensity beams and machines (from [84]).*

Experiments using intense beams offer unique and unprecedented access to the dark sector with possible discoveries of specific dark matter candidates. The characteristics of low mass and weak couplings of these exotic particles make Intensity Frontier experiments particularly suited to this kind of physics. An overview of the many experiments proposed to explore the dark sector in intense beams and machines is presented in Fig. 9-4. A key aspect of this physics program is the continued exploitation of already existing large multipurpose detectors, especially Belle-II and LHCb, to study dark sector states. In addition, dedicated efforts at high-intensity accelerators have started. A Basic Research Needs (BRN) workshop on Dark Matter New Initiatives identified the study of dark matter particles and associated forces below the proton

mass, leveraging DOE accelerators that produce beams of energetic particles [12]. This workshop resulted in support for two experiments. One of them, Coherent CAPTAIN-Mills (CCM) [85], is a beam dump experiment employing the 800-MeV proton beam at the Los Alamos Science Center (LANSCE). It uses a large liquid argon fast detector and timing synchronization with the source to reject background. An improved detector (CCM200) with 200 inner PMTs and a purification system to achieve lower thresholds began taking beam and calibration data in 2021 and has started operation. The second one is LDMX [86], an electron fixed-target experiment that searches for sub-GeV dark matter via the missing momentum technique at the Linac to End Station A (LESA) facility at SLAC. It utilizes a W or Al target surrounded by a hermetic detector and searches for a massive particle that can escape without depositing significant energy in the detector. It has received pre-project funds and needs further support to become operational. In addition, a promising set of experiments has been identified since the last P5 report [13,84]. Dark-sector theory will also be critical both to continue developing dark-sector models to address open problems in particle physics and cosmology and to maximize the efficacy of the experimental program, where the track record of theorists pioneering new approaches is strong.

A vibrant program of new physics searches in rare μ decays is currently ongoing in Europe (PSI) and Japan (J-PARC) and is about to start in the U.S. (Mu2e). An approximate timeline is presented in Fig. 9-5. The PSI program currently consists of the MEG-II experiment, searching for the decay $\mu^+ \to e^+\gamma$, and Mu3e, searching for $\mu^+ \to e^+e^+e^-$ in muon decay. MEG-II is an upgrade of the MEG experiment and will collect its data starting in 2022 [89]. Mu3e Phase I will take data by the middle of the decade. The HiMB upgrade at PSI will enable about an order of magnitude improvement in the discovery potential for Phase-II of the Mu3e experiment starting around 2028 [90,91]. However, a new experimental concept will be required for MEG to use the improved HiMB beam [92].

The third muon CLFV process, coherent muon-to-electron conversion $\mu^- N \to e^- N$, will be pursued by the Mu2e and COMET experiments beginning around 2025, at FNAL and J-PARC respectively. Assuming $\mathcal{O}(1)$ couplings in the EFT Lagrangian for new physics in these decays, the experiments described here will probe mass scales for dimension-6 magnetic dipole operators at a few $\times 10^3$ TeV/c^2. Muon-to-electron conversion and $\mu \to 3e$ are sensitive to more operators than $\mu \to e\gamma$. Both COMET and Mu2e can reach mass scales of $\mathcal{O}(10^4)$ TeV/c^2 in dimension-6 contact terms. We also note that Mu2e and, to a lesser extent, COMET can probe the $\Delta L = 2$ process $\mu^- N \to e^+ N'$, which is sensitive to new particles such as leptoquarks and is related to neutrinoless double-beta decay through the Schechter-Valle theorem [93].

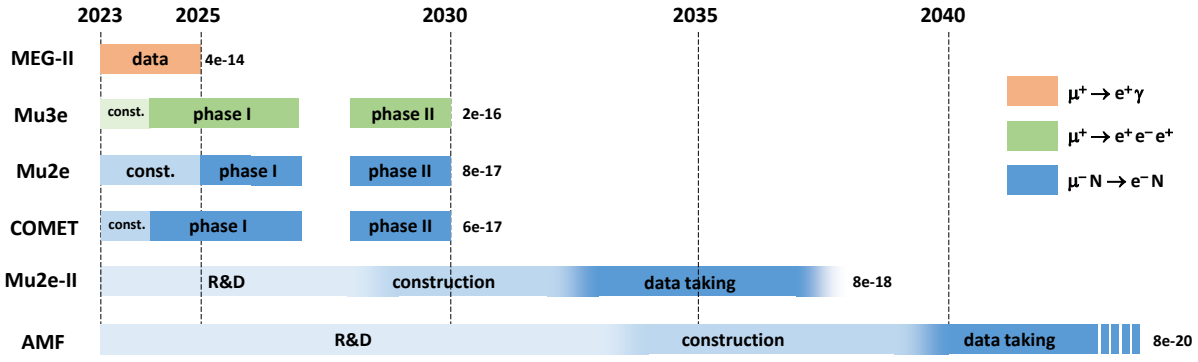

Figure 9-5. *Timeline for muon-based charged lepton flavor violation experiments discussed in this report. Approximate expected dates are shown. The number to the right of the timeline is the expected final 90% CL.*

The U.S. program focuses on the muon conversion process $\mu^- N \to e^- N$. The possibility of utilizing different targets may elucidate the nature of the new physics possibly unveiled through studying these decays. In addition, the combination of results obtained studying these decays with results from experiments studying $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$ transitions may pin down the source of new physics. The Mu2e experiment, recommended by the previous P5 panel, is currently being constructed. Mu2e will have its first run at lower beam intensity in 2025, just before the LBNF/PIP-II shutdown. Its goal is to improve by about four orders of magnitude upon the limit on the parameter $R_{\mu e}$ obtained by the SINDRUM II experiment at PSI [94]. The key features of the Mu2e experiment are a high-resolution tracking system and a calorimeter placed inside a solenoid. The muon transport line is based on curved solenoids to shield the detector from the direct line of sight of the production target and select negatively charged muons. In parallel, the Mu2e experiment is investigating an upgrade (Mu2e-II at PIP-II) that can enhance their sensitivity by about a factor of ten, beginning with an increase of the beam power from 8 kW to 100 kW [27]. The detector and beamline will then have to cope with increased radiation and backgrounds. Studies of production solenoid modifications, along with a reduction of material in the tracking relative to Mu2e, along with novel and faster calorimeter materials, are key goals of the proposed R&D [27]. In the longer term the suggested AMF facility will require significant R&D; some of these efforts, in particular high-power targeting inside a solenoid, are related to R&D for the muon collider [28].

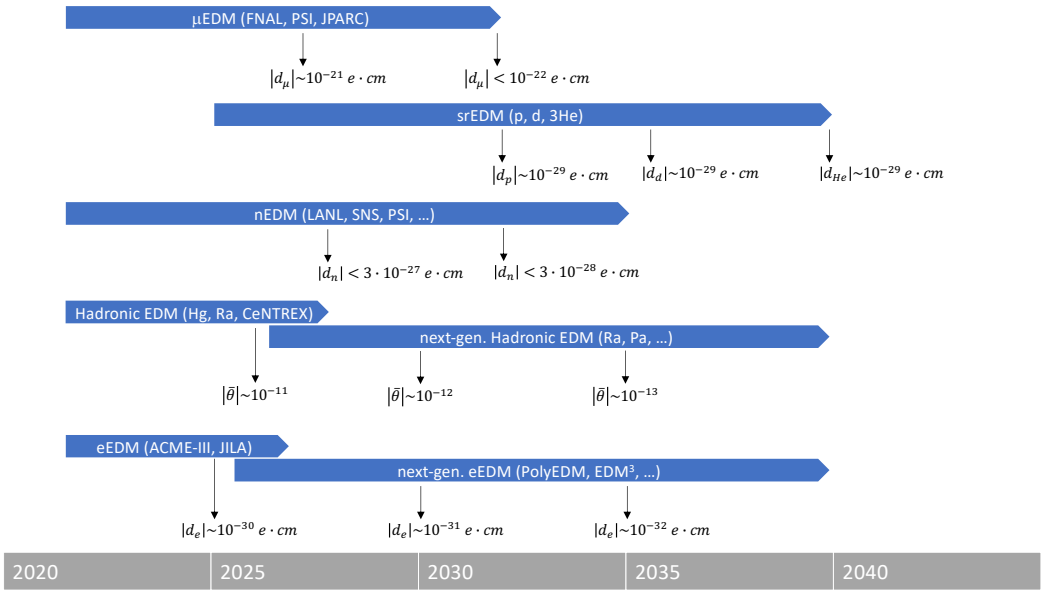

Figure 9-6. *Timelines for the major current and planned EDM searches. Their measurement goals are indicated by the black arrows, based on the current plans of the various groups. The Storage Ring proton EDM experiments highlighted in this report are labeled "srEDM."*

Flavor-conserving processes such as the muon anomalous magnetic moment, or electric dipole moments (EDMs) of any system (electron, muon, neutron, proton, atom, or molecule), would represent an exciting manifestation of new physics. As a part of the Snowmass process, the current landscape of proposed electrical dipole moment measurements has been examined [21]. The search for the neutron EDM started

by Ramsey and Purcell [95] has reached a precision of $(0.00 \pm 1.1|_{\rm stat} \pm 0.2|_{\rm sys}) \times 10^{-26} e \cdot$ cm [96]. Atoms and molecules have been increasingly powerful EDM probes, exploring CP violation through EDMs, and several searches leveraging techniques developed in AMO physics have been proposed in order to increase the sensitivity by a factor of 10 in the near-term time scale, ultimately aspiring to achieve a four-to-six order of magnitude improvements in a 15–20-year time scale, exploiting progress in quantum science techniques, and availability of exotic nuclei, made possible by advances in nuclear physics. A new approach is the proposed EDM measurement at a storage ring [20, 21]. This technique, inspired by the method used to measure the anomalous magnetic moment of the muon, has the goal of reaching a proton EDM sensitivity of $10^{-29} e \cdot$ cm while probing other fundamental quantities, such as CPV in the Higgs sector, and improving current limits on $\theta_{\rm QCD}$ by three orders of magnitude. A timeline for EDM experiments is given in Fig. 9-6.

Finally, violations of discrete conservation laws, such as baryon number or lepton number, or B–L, which are preserved by the SM, are a pillar of the experimental program described here. Their study supports our understanding of the baryon asymmetry in the universe, with the consequent disappearance of antimatter. Thus the search for proton decay with an increased sensitivity, an integral component of the DUNE and Hyper-Kamiokande physics programs, is closely connected with the themes and big questions we are investigating in this Frontier. In addition, the nature of the neutrino species, and whether they are Dirac, Majorana, or a mixture of these two, is a fundamental question in particle physics. We have shown how some of the experiments described so far can investigate heavy Majorana neutrinos and baryon oscillations. A landmark set of measurements that can elucidate whether light neutrinos are Majorana or Dirac particles is based on studies of neutrinoless double-beta decays. Because of their nature, they are an investment of the experimental nuclear physics community, but there is an extensive and profound synergy with the high-energy physics community that is equally interested in this fundamental question. In particular, the "multi Tonne" scale experiments that plan to reach a sensitivity of $T_{1/2} = 10^{28}$ years naturally lend themselves to shared HEP and NP efforts. Achieving this goal will require optimizing the energy resolution of the detector, reducing backgrounds, and measuring residual backgrounds with high efficiency. Only then can the experiment build a precise background model and provide a reliable estimate of the experiment's sensitivity. These are areas where experience in the high-energy physics community is crucial. On the other hand, the experimental methods and calculations required for studying a variety of isotopes are the provinces of nuclear physics. Thus a fruiful collaboration between these two communities would greatly aid the successful implementation of this fundamental physics program.

9.4 R&D for the Rare and Precision Frontier

Realizing the experiments described in this report [9] requires R&D in both accelerators and instrumentation. The muon program requires targeted accelerator R&D on three fronts. The Accelerator Frontier AF5 report on "Accelerators for Rare Processes and Physics Beyond Colliders" discusses many of these issues in more detail [97]:

- A compressor ring to rebunch the PIP-II beam. The ring should be designed to support both the muon program and a dark-matter beam dump experiment. A particular challenge here is the kickers that need to operate at up to about 40 kHz [28].
- a fixed-field alternating gradient synchrotron to serve as a muon storage ring. A prototype has been constructed at Osaka [98].
- The experimental program requires targeting the PIP-II beam at ≥ 100 kW inside a superconducting solenoid, with an ultimate goal of 1 MW of power, well-matched to PIP-II. Achieving 1 MW will require an upgrade to or replacement of the Fermilab Booster, enabling a wide range of physics [99].

The problem shares many aspects with some schemes suggested for targeting for a muon collider; this program could then serve as a "test bed" for muon collider R&D [100–102].

The experiments examined in this frontier can be grouped into four broad categories: experiments studying interesting quark transitions and τ lepton decays, experiments searching for lepton flavor violation in μ decays, experiments searching for EDMs, and dark sector at high-intensity experiments. We will now consider some of the instrumentation R&D required for this program.

Table 9-2 summarizes the major detector R&D requirements of these experiments, organized in terms of solid-state tracking devices, gaseous tracking devices, calorimetry, VLSI electronics, trigger and data acquisition, and quantum sensors in the medium-term.

A common theme in several of these experiments is the importance of precision timing information, with a resolution of the order of tens of picoseconds, to reduce combinatorial backgrounds associated with multiple interactions per crossing in high luminosity hadron machines or as a tool for out-of-time background suppression.

Increasing the luminosity to reach higher sensitivities also implies unprecedented radiation fluence. For example, the LHCb upgrade 2 will withstand fluences up to $5 \times 10^{16} \mathrm{n_{eq}/cm^2}$ during its nominal running time. Even in e^+e^- high luminosity colliders such as Belle II, the ambitious upgrade planning makes radiation hardness an important consideration.

Table 9-2. *Detector specifications for representative RPF experiments (medium term goals)*

Experimental approach	Technology	Property	Requirement
Quark flavor experiments	Solid State Tracking Detectors	Time stamp Radiation hardness	10–30ps/hit in the silicon pixel vertex detector fluences up to $5 \times 10^{16} \mathrm{n_{eq}/cm^2}$
	Calorimetry	Time stamp resolution	10-30 ps/shower
	Trigger & DAQ	Real time processing Optical links	400-500 TB/sec Radiation-hard, fast, low-power and low-mass
LFV experiments (μ)	Staw Tube Tracker	timing	20 ps/track, low-mass, excellent momentum resolution
	Calorimetry	Energy resolution timing	$< 10\%/\sqrt{E}$, low cost Shower time stamp < 500 ps, dose > 900 KRad
EDMs	Controlled preparation of many coherent particles	coherence times	$\tau \geq 1s$ or $N >> 10^{12}$
	Laser locking, tuning and linewidth narrowing (many narrow-band lasers on target)	tunable narrow band	< 1 MHz, $\lambda = 2002 - 400$nm
Dark Sector (missing energy technique)	E&M calorimetry	Energy resolution	
Dark Sector (Beam Dump experiments)	photosensors	fast-timing photosensors	

Operation at ever-increasing luminosity and the correspondingly harsher environments will pose several challenges for the front-end electronics. The need to incorporate higher and higher complexity in devices that need to sustain higher radiation fluences implies the use of a variety of technologies, such as CMOS devices with ever-smaller feature sizes and possible alternatives to CMOS technologies. The effort to understand the transistor parameters of different technologies and to streamline the design to avoid prohibitive development costs is common to many of the projects described here. This is one of the most promising targets of a national R&D program, where a multi-frontier collaborative efforts are established to develop the technologies needed to accomplish the broad scientific goals of the US high-energy physics community [103].

On a longer time scale, all these requirements will apply but with more stringent specifications. For example, the Mu2e-II experiment will require "transparent tracking" with a reduction of the 15μm straw walls down to 8μm and faster and more radiation-hard crystal calorimeters. Quark flavor experiments implemented at a high energy and luminosity e^+e^- collider will require a timing resolution at the level of 1 ps per track for πpK separation. Radiation requirements will be pushed to $10^{18}\mathrm{n_{eq}/cm^2}$. The energy resolution and background suppression required by the dark sector experiments utilizing a missing energy technique are synergistic with some of the technology efforts described here. Experiments pursuing EDM measurements and other precision tests of fundamental laws are leveraging the progress in AMO techniques and quantum sensors to exploit a broader array of probes, a variety of molecules and different nuclei (some of them with extreme properties such as high angular momentum), and bigger samples with longer coherence times. The combination of these efforts is building a foundation for an era of discovery [82].

9.5 The Role of Theory

The primary strategies for indirect searches of New Physics particles proceed along three main directions: (1) studies of processes that are not allowed in the Standard Model, (2) studies of processes that are not allowed in the Standard Model at the tree level, and (3) studies of the processes that are allowed in the Standard Model. While virtual effects associated with new particles can probe energy scales beyond direct detection experiments (see, e.g., Fig. 9-7), there are low-energy SM contributions that can potentially mask or even overwhelm such effects. Thus, proper interpretation of experimental results is crucial in searching for New Physics phenomena.

The role of theory in the unambiguous interpretation of the results of experiments and requirements for theoretical methods used in the analyses have significantly changed over the last thirty years, shifting from model estimates and quenched lattice QCD calculations to rigorous approaches with improvable computations of theoretical uncertainties [106, 107]. The theoretical interpretation of experimental data often relies on the computation of matrix elements of operators of some effective Lagrangian $\mathcal{L}$. The construction of those operators and the required calculations of matrix elements rely on a separation of the physical scales often present in a problem. The methods of Effective Field Theories allow relating physics at different scales by performing matching and employing the running of the renormalization group [108].

Theoretical methods applied to interpreting experimental data often depend on the assumption about the properties of NP particles, in particular on the energy scale at which NP degrees of freedom can propagate on-shell. The EFT techniques allow for incorporating this fact into the computations directly.

For heavy NP, the masses of all NP particles are larger than the energy scales associated with an experiment. Explicit modeling of New Physics effects allows one to conjecture a fundamental mechanism that could have implications for the low- and medium-energy phenomena. Examples of such modeling include multi-Higgs or leptoquark models with flavor-changing neutral current interactions [109] (see [7] for a recent review of the

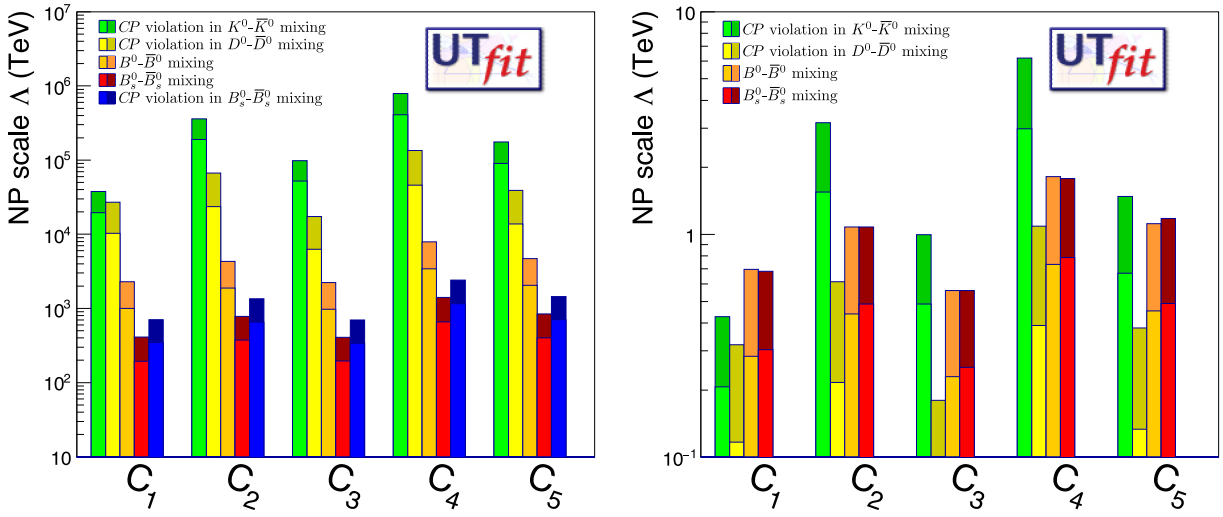

Figure 9-7. *Present (lighter) and future (darker) lower bounds at 95% confidence level on the NP scale Λ from $\Delta F = 2$ transitions [104, 105]. The Wilson coefficients $C_i = F_i L_i/\Lambda^2$ $(i = 1, ..., 5)$ are the coupling of the NP dimension-six operators governing the $\Delta F = 2$ transition: $Q_1^{q_i q_j} = (\bar{q}^\alpha_{jL}\gamma_\mu q^\alpha_{iL})(\bar{q}^\beta_{jL}\gamma^\mu q^\beta_{iL})$, $Q_2^{q_i q_j} = (\bar{q}^\alpha_{jR} q^\alpha_{iL})(\bar{q}^\beta_{jR} q^\beta_{iL})$, $Q_3^{q_i q_j} = (\bar{q}^\alpha_{jR} q^\beta_{iL})(\bar{q}^\beta_{jR} q^\alpha_{iL})$, $Q_4^{q_i q_j} = (\bar{q}^\alpha_{jR} q^\alpha_{iL})(\bar{q}^\beta_{jL} q^\beta_{iR})$, and $Q_5^{q_i q_j} = (\bar{q}^\alpha_{jR} q^\beta_{iL})(\bar{q}^\beta_{jL} q^\alpha_{iR})$ (with α and β being color indices). On the left, NP is assumed to have arbitrary flavor structure ($F_i = 1$) and to be strongly coupled with no loop suppression ($L_i = 1$); on the right, NP is assumed to have minimal-flavor-violation couplings ($F_i = V_{\rm CKM}$) and to enter at one loop with weak coupling ($L_i = \alpha_2^2$, with α_2^2 being the weak structure constant). The future bounds are based on expected sensitivities at Belle II (50 ab^{-1}), BESIII, LHCb Upgrade II (300 fb^1), and ATLAS/CMS (3 ab^{-1}), and on improved theory inputs (from [31]).*

models) or models of Grand Unification that contain new particles mediating baryon- and lepton-number violating interactions [110, 111] (see [112] for a recent review of the models). Such explicit models are extensively discussed in the Topical Group reports [7, 7, 9, 14, 31, 113].

No on-shell propagation of NP particles is possible at energy scales below the masses of such new particles. In that case, the effects of NP can be approximated by a series of operators of increasing dimension multiplied by Wilson coefficients encoding the effects of NP particles:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{i,n} \frac{C_{i,n}(\mu)}{\Lambda^n} Q_i^{(n)}(\mu), \tag{9.1}$$

where Λ parameterizes the scale at which New Physics becomes operational and $C_{i,n}$ represents the Wilson coefficients, which are given by a combination of coupling constants and other factors. Each model of NP provides different combinations of factors. The EFT methods are uniquely suited to computations of indirect effects of new physics, as the construction of Eq. (9.1) parameterizes *all* BSM models that can contribute to a given process.

The momentum scale μ in Eq. (9.1), somewhat artificially, divides the short-distance physics encoded in the Wilson coefficients and the long-distance physics that corresponds to the computation of matrix elements of effective operators $Q_i^{(n)}(\mu)$. The process of relating higher-energy operators to lower-energy operators, which involves removing non-propagating degrees of freedom, is called matching. Depending on the problem, the matching can be done perturbatively or non-perturbatively.

Since the EFT method is designed to capture the effects of all heavy NP particles, the construction of an effective Lagrangian at each order in n can be done by choosing a particular power counting scheme and writing the most general basis of operators consistent with the symmetries of the theory. This procedure is non-trivial, especially at higher orders in n, where the number of possible operators grows rapidly. Minimal bases of the operators in the Standard Model Effective Field Theory (SMEFT) that are invariant under the SM gauge group have been partially constructed for the operators of dimensions 6,7, and 8 [108]. Some higher-dimensional operators describing the baryon-number violating interactions at low energy have also been constructed [108, 114–116], as they represent the leading order at which those interactions can be encoded. Anomalous dimensions of those operators, which determine perturbative relations between operators at different scales, have also been computed for the dimension 6 operators in SMEFT [117–119]. While the SMEFT power counting scheme is the most straightforward, with the importance of operators encoded in the operator dimension, other power counting schemes have also been explored [120].

If the NP particles are light, i.e., their masses are comparable to or smaller than the energy scales at which an experiment is performed, they must be explicitly included in the construction of effective operators. This is often the case for the Dark Sector models containing axions, dark photons, right-handed neutrinos, etc. Explicit operators of the lowest dimension coupling such particles to the SM fields have been classified and go under the name of portals [14].

Relating an effective Lagrangian to a physical process usually involves computations of process-dependent matrix elements of effective operators encoded in that Lagrangian. This often represents the most delicate part of the calculation.

Some matrix elements can be perturbatively computed, such as those involving only weakly-interacting particles. Examples include processes with leptons in the initial and final states, atomic transitions, or muonium-antimuonium oscillations, where the leading-order matrix elements can be computed in QED. Non-perturbative QED effects are reasonably under control, with the relevant wave functions obtained from the analytic or numerical solutions of the Schrodinger equation. It must be pointed out, however, that further improvements are required in the treatment of QED corrections to many processes, including those involving strongly-interacting particles [7].

The most challenging processes involve strongly-interacting particles, where the computation of the relevant matrix elements yields the largest theoretical uncertainties. Theoretical methods employed to deal with such matrix elements largely depend on the physical system under consideration. They include lattice QCD, various QCD sum-rule techniques, phenomenological fits, and quark model techniques [121]. The importance of systematically-improvable computational techniques is recognized in the theory community. In the previous decade, this led to extensive development of lattice QCD techniques, which represent numerical solutions of QCD in Euclidean space. Lattice QCD calculations achieved remarkable precision for some of the quantities representing matrix elements of quark currents. For example, decay constants and semileptonic form-factors for pions and kaons are known with sub-percent accuracy [122]; similarly precise results are available for the decay constants of $B_{(s)}$ mesons [7, 122]. In addition, the lattice-QCD community is studying increasingly more complicated quantities, such as nonlocal matrix elements, multi-hadron matrix elements, and inclusive decay rates [107, 122]. At the percent-level many other phenomenologically relevant results have been obtained, including quark masses, bag parameters for neutral meson mixing, and form factors for semileptonic decays of heavy mesons and baryons, with further improvements expected in the near future [122, 123].

While the model-independence of other methods, such as QCD sum rule techniques, is often debated, they represent an approximate solution of QCD in Euclidean space and are based on the operator product expansion techniques [124], which require more independent inputs at increased precision levels. The issues often raised concern the stability of sum rules with respect to the so-called Borel parameter or reliance on

various versions of quark-hadron duality. Nevertheless, QCD sum rule analyses often provided estimates of physics observables long before lattice results were available [124].

Sometimes the internal symmetries of the system allow for additional simplifications. For example, transitions involving heavy quark systems, mesons, and baryons involve several momentum scales, such as the scale associated with the mass of the heavy quark, m_Q, and the QCD intrinsic scale $\Lambda_{\rm QCD}$. The methods of heavy quark effective theory (HQET) allow us to relate various matrix elements in the heavy quark limit by expanding them in the ratio $\Lambda_{\rm QCD}/m_Q$ [7,31]. Higher order corrections associated with such expansion often depend on soft matrix elements 9-8 that can be computed in lattice QCD, QCD sum rules, or fit to experimental data [7].

Treatments of more complicated multi-scale problems with heavy quarks have also been developed and applied to quarkonium systems (Non-Relativistic QCD (NRQCD)) and non-leptonic decays of heavy hadrons (Soft-Collinear Effective Theory (SCET)). Other internal symmetries, such as isospin or flavor SU(3), can also be employed to reduce the number of unknown parameters. One should point out that the resummation methods of SCET have also been applied to study QED effects, in particular to soft or collinear photons that can lead to large logarithms and to hadronic structure-dependent effects in leptonic and semileptonic transitions [7].

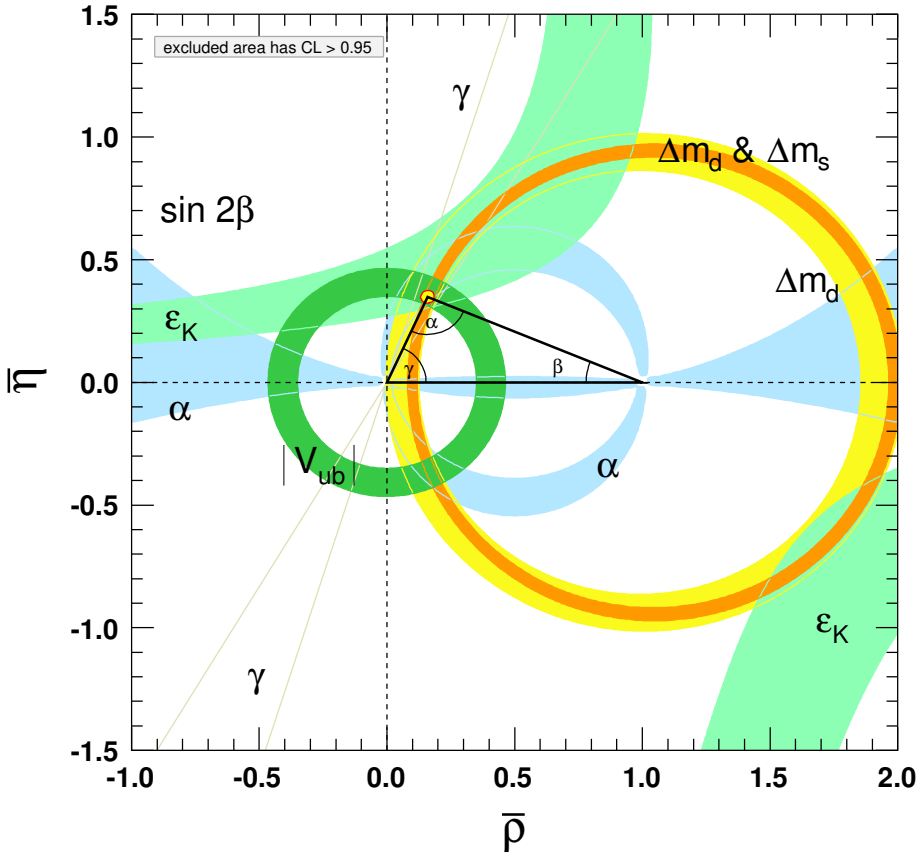

Figure 9-8. *Various indirect studies of New Physics can be combined to provide constraints on both SM and BSM parameters. An example is studies of the CKM unitarity triangle [35] , which requires precise knowledge of nonperturbative parameters.*

Computations of transitions involving the light-quark systems can sometimes be simplified by applying chiral symmetry arguments [125]. Chiral Perturbation Theory (χPT) techniques allow for controllable expansions of transition matrix elements in powers of E/Λ_χ, where E is the energy scale associated with the transition, and $\Lambda_\chi \simeq 1$ GeV is the chiral symmetry breaking scale in QCD. External parameters of χPT, the low energy constants, can be obtained from the experimental fits or direct lattice QCD calculations [125].

While some of the experimental observables, such as anomalous magnetic moments a_ℓ, leptonic electric dipole moments d_ℓ, or lepton-flavor violating transitions among leptons, do not involve strongly-interacting particles in the initial or final state, their effects do come into computations of perturbative electroweak corrections. For example, a theoretically-controlled calculation of the hadronic vacuum polarization (HVP) contribution to the anomalous magnetic moment of the muon a_μ, which constitutes the largest theoretical uncertainty in computing this quantity, is crucial in understanding the source of the disparity between the theoretical predictions and experimental measurements [113]. The results of sophisticated computations of HVP using continuum methods [126] are currently in tension with the direct lattice QCD calculation by the BMW collaboration [127]. It is expected that new, precise results for HVP from other lattice collaborations as well as new experimental measurements of the low-energy e^+e^- hadronic cross sections will shed light on this tension in the coming years [128].

The largest theoretical uncertainties affect the interpretation of experimental data involving nuclei. Sometimes, symmetry arguments can be used to remove the computations of nuclear matrix elements, as in the case of transitions between 0^+ nuclei used to extract the CKM matrix element V_{ud}. However, explicit computations are still required for the sub-leading effects [125]. In general, the computations of nuclear effects are done with the help of nuclear models. Unfortunately, such computations can only provide an estimate of theoretical uncertainties. Examples of such processes include muon-to-electron conversion $\mu^- N \to e^- N$ [9] or neutrinoless double beta decay $A(Z) \to A(Z+2)e^-e^-$ [112]. In both examples, even the observation of the transition would indicate the presence of New Physics.

Theoretical research also plays an important role in the computations of background processes. Two such calculations that will be important are the evaluations of radiative pion and radiative muon capture in the Mu2e and COMET experiments. Both processes are irrelevant for NP searches but constitute backgrounds that need to be understood. The radiative pion capture process can have the same experimental signature as muon-to-electron conversion $\mu^- N \to e^- N$. Radiative muon capture has an endpoint well below the muon-to-electron conversion signal but is a potential problem for measurements of the $\Delta L = 2$ process $\mu^- N \to e^+ N'(Z-2)$.

The community recognizes the value of multi-institution theory efforts connecting high-energy physics and nuclear physics communities; the Neutrino Theory Network is one such program that is accelerating progress [129]. Such multi-institutional efforts are common in collaborations working with lattice formulations of QCD on high-performance computers. Some examples of such collaborations include the Fermilab Lattice, HPQCD, MILC, and RBC-UKQCD Collaborations. The majority of US physicists working in lattice formulations of QCD are also members of the USQCD collaboration, whose software resources are open-source and widely used by the worldwide community [7]. Different lattice groups also cooperate to provide important inputs for experimental measurements, e.g., the Flavour Lattice Averaging Group (FLAG) [130].

Another important synergy is based on collaborative interactions between the theory community and experimental collaborations. Such activities have proven to be important engines for both communities. There are several examples; in particular we note the Heavy Flavor Averaging Group (HFLAV), that periodically provides updates of properties of heavy-flavored states and their transitions [131], the Muon g-2 Theory Initiative [126], and the Joint Physics Analysis Center (JPAC) at Indiana University studying properties of exotic states of the hadrons [132].

Continued support for leadership in dark-sector theory is also critical both for developing models to address open problems in particle physics and cosmology, and for maximizing the efficacy of the dark-sector experimental program [14].

Indirect studies of BSM physics currently provide the most stringent constraints on the possible scale of New Physics, as well as several observables whose values exhibit intriguing deviations from the SM expectations. A robust US theory program, which supports both researchers and computing resources, is essential for properly interpreting such experiments.

9.6 Connections with Other Fields

All the Frontiers have connections to other fields inside and outside particle physics. Mechanical engineering, electrical engineering, and materials science are integral components of the experimental program in particle physics, where state-of-the-art technologies continue to be tools of discovery. Advances in computer science are critical data processing and data mining in experimental particle physics and their interpretation with precise theoretical interpretation and prediction tools. The diversity of topics and techniques in the Rare and Precision Frontier leads to a multifaceted web of profound connections. Here we focus on a few examples to illustrate how more cross-disciplinary efforts would benefit HEP.

9.6.1 Connection With Other Frontiers

Energy Frontier First, the Energy Frontier hopes to produce particles signaling new physics that might explain observations in other Frontiers. For example, the discovery of SUSY or leptoquarks could explain a discovery in charged lepton flavor violation, the B-anomalies, or the muon $g-2$ result. Many such examples could be added. The breadth of capabilities of the general-purpose Energy Frontier detectors allows them to pursue some measurements that are synergistic with RPF studies. For example, DM particles can be produced in high-energy collisions in energy ranges complementary to RPF experiments focusing on masses between 1 MeV/c^2 – 1 GeV/c^2 [133]. New experiments such as CODEX-b, Faser 2, or MATHUSLA have been proposed to use high-energy collisions to search for long-lived dark matter particles [8]. Rare b hadron decays with final states involving charged muons can be measured with high precision. Specific hadron spectroscopy studies can be carried out at either e^+e^- colliders or Energy Frontier pp machines [31].

Neutrino Physics Frontier There are two areas of connection to the Neutrino Frontier. First, finding $0\nu2\beta$ would tell us that neutrinos are Majorana particles. Complex neutrino Majorana phases can yield leptogenesis, which can then produce baryogenesis [23]. Although we cannot predict the matter-antimatter asymmetry from Majorana phases, finding that neutrinos are Majorana particles combined with a non-zero CP δ would be suggestive. Current neutrinoless double-beta decay experiments provide a lower limit of 3×10^{25} years [134] and are covered in our topical group of Baryon and Lepton Number Violation. Second, there is a natural overlap between neutrino physics and charged lepton flavor violation, another of our topical groups. Here, the simplicity of the Standard Model does not explain obvious questions: why do the neutral leptons (neutrinos) change flavor when their charged partners apparently do not? If there is mixing, what is the mixing matrix that corresponds to the PMNS matrix for the charged leptons, and what is its structure? In a broader context, masses and mixing parameters among quark and leptons constitute a set of SM parameters with patterns and hierarchies that we do not understand. It is a hope that the concerted efforts of the RPF and NF frontiers will lead to a unified picture of the underlying physics. Finally, the dark sector efforts

described in this report can leverage detector techniques relevant to the neutrino frontier. In addition, dark bosons may couple to neutrinos, making it possible for neutrino physics experiments to elucidate this sector about which so much is not yet known.

Cosmic Frontier The most immediate connection to the Cosmic Frontier comes from the search for dark matter, which is a focus of the RPF. In addition, the search for lepton and baryon number violation in heavy baryon oscillations or new sources of CP violation can provide clues on the origin of the baryon asymmetry of the universe. As we will see in the discussion of connections to AMO and nuclear physics, RPF connects to AMO through interferometry that can search for gravitational waves, certainly a topic of the Cosmic Frontier.

Theory Frontier Theory is essential in every experimental frontier to provide an intellectual structure, motivations for new experiments, calculations, and interpretation of experimental results. We wish to stress two connections. Effective Field Theories are especially useful in RPF experiments, since the RPF focuses on indirect searches for physics at unknown mass scales. EFTs are a natural method for categorizing contributions from different sources and interpreting data [106, 121]. The other special connection for our Frontier is Lattice QCD. Lattice QCD calculations relate our studies of all the hadron decays to fundamental quantities such as absolute values of CKM angles and predict SM expectations for rare decays, evaluate matrix elements relevant to the $g-2$ anomaly, and predict mass spectra of hadron multiplets [107]. They are essential to extract fundamental properties with systematically improvable and well-understood theoretical uncertainties.

Accelerator Frontier RPF especially connects to the Accelerator Frontier subgroup "Accelerators for Rare Processes and Physics Beyond Colliders." [97] Restricting our comments to that subgroup, a new muon program using PIP-II requires a new and unique fixed-field alternating gradient synchrotron (FFA), leading to a future muon program that explores low-energy muon physics and charged lepton flavor violation.

Instrumentation Frontier Advances in instrumentation are essential for progress in several of our topics.

The instrumentation frontier is organized into ten topical groups:

- Quantum sensors, which leverage quantum phenomena to make measurements by manipulating quantum states, entanglement, superposition, and similar approaches.
- Photon detectors, which covers photon detection at all wavelengths, from gamma ray, visible, and ultimately radio.
- Solid State Detectors and Tracking covers solid state sensors for tracking detectors, from silicon to diamond and other alternative materials. It also covers non-solid state trackers such as straw trackers for high-intensity experiments.
- Trigger and data acquisition systems, which are tasked with collecting data from the front-end devices, reducing the data volume through selection algorithms, and producing high-level quantities for further processing. Their scope includes technologies to transform electrical to optical signals and synchronization mechanisms for the precise time alignment of different components.
- Micropattern and gas detectors, which recent developments and future needs for Micro-Pattern Gaseous Detector (MPGD) technologies, driven by the availability of modern photolithographic techniques.
- Calorimetry, namely the measurement of particle energy, in particular the energy of photons and π^0's.

- Electronics and ASICs for signal processing and data aggregation. The goal is to allow higher active element density, enhanced performance, lower power consumption, lower mass, higher radiation tolerance, or performance at cryogenic temperature.
- Noble elements, covering the use of noble elements for particle detection in the gas, liquid, or solid phases, as well as other similar techniques. Included technologies include TPCs at large and small scales, which include the measurement of scintillation, ionization, and other interaction signatures.
- Cross-cutting and system integration, examining the connections between the instrumentation components summarized here and different experimental efforts, as well as considering the aspect involved with large system integration and the infrastructure needed to carry out this work, such as test beam facilities or irradiation facilities.
- Radio-wave detection.

High-precision timing ($\mathcal{O}$(10ps)) is an increasingly essential feature that connects tracking detectors, calorimetry, and data acquisition systems and influences the performance of several experiments considered here. For example, the LHCb Phase II upgrade, with its high occupancy environment, leverages the association of tracks and showers with the right primary vertex to process the events more efficiently, with a highly reduced combinatorial background.

An overall optimization of the material budget is key to the performance of most of the systems described in the experimental section. It is epitomized by the ultimate goal of a "transparent tracker" in future upgrades of the Mu2e experiment, sensitive to 105 MeV/c electrons or the $\mu \to e\gamma$ and $\mu \to 3e$ experiments especially sensitive to electrons near the Michel peak at 52.8 MeV/c. These low-energy electrons suffer large multiple scattering and dE/dx relative to the high-energy particles observed in many other experiments.

Particle identification is an essential feature of heavy flavor experiments. Future needs include radiation-hard, fast, and cost-effective photosensors. Some of these needs are shared by dark sector experiments.

This highly abbreviated description is only meant to showcase the profound connection between the physics goals of the RPF frontier and the goals of the instrumentation frontier to develop new detector elements, front-end electronics, and trigger and data acquisition systems. Many of these technologies affect the performance of detectors planned for many different frontiers. New investments and long-term commitment to advances in instrumentation, along with the exploitation of synergies and the development of interdisciplinary research efforts, are essential for progress in all of particle physics.

Computational Frontier Computing connects to all the Frontiers, and RPF has many connections to computing:

- Lattice QCD is an essential tool across our Frontier. Computing time is a significant issue in improving Lattice calculations. An important question a Lattice theorist often will ask about a prediction is "how much computing time did it take?" as part of their evaluation of the quality of the calculation. Current simulation goals require more than an order-of-magnitude improvement in performance. [135]
- There are many detector and physics simulation challenges that need to be addressed, summarized in Ref. [136], although this article is oriented toward Energy Frontier and heavy flavor experiments rather than low-energy experiments. We touch on a few:
  - The RPF wants to send a strong and emphatic message, also discussed in the Computing Frontier report: GEANT4 is not sufficiently supported in the U.S. The physics models of

some crucial processes, including but not limited to their cross-sections, rates, and spectra, are in disrepair [137, 138]. The core group at SLAC has largely retired and there is no identified funding source. Many experiments in RPF rely on low-energy phenomena whose simulations are not kept up to date; when bugs and errors are found, they are not fixed because there is no one to fix them. GEANT is infrastructure akin to "roads and bridges"; the current trajectory endangers progress across particle physics.

- Heterogeneous architectures present significant challenges for HEP software. GPU and FPGA manufacturers tend to use their own software stacks, requiring specialized knowledge. HEP programmers are usually trained in C++. While cross-platform tools are being developed, taking advantage of the options requires re-writing large fractions of the HEP software stack. Furthermore, most HEP code bases are not easily vectorizable or parallelizable. Problems such as particle transport are difficult to run on GPUs because of thread divergence. Taking advantage of the massive data flows from experiments such as LHCb (restricting ourselves to the RPF) requires fundamental change and new resources.
- LHCb has moved to a largely triggerless model where offline processing is performed in real-time. Such a system is more efficient since offline flows are pushed online, decreasing storage requirements, and allows a data taking approach that can be optimized for specific physics goals. This model of single-pass, real-time execution is very attractive and enhances its discovery potential. It must feature robust real-time reconstruction and calibration algorithms.

We note a common issue that affects many of the above points: there has been a major drop in funding for permanent positions in HEP that allow researchers to work on both experiment-specific tools and general issues. Computing Frontier Group 2 addresses these problems for Lattice QCD, event generators, and GEANT, and we strongly endorse their calls for action [139].

Underground Facilities Frontier RPF does not require new underground facilities beyond those already planned in conjunction with the Neutrino Frontier for low cosmic-ray background experiments such as neutrinoless double-beta decay searches.

Community Engagement Frontier The Community Engagement Frontier and RPF share the goal of improving the communication of our science to the public. High-profile analyses that can be linked to broad themes that capture the public's imagination have been very successful in connecting the general public with some flagship results. We give a few examples here. Anomalies hinting at possible new physics manifestations received a lot of attention. The $g-2$ experiment was a rare breakthrough for our field — the story of the ring's travels from BNL to Fermilab unquestionably engaged the public. Discoveries of exotic hadrons such as pentaquarks and tetraquarks received much attention. In times when attention to scientific achievements may be less prominent, we need to leverage these successes and broaden the connection between captivating themes and more specialized and abstract studies that are perhaps more difficult to explain. A more systematic approach to developing shared material and creative new communication tools is needed to improve the connection between scientists and the public, as well as strengthen advocacy efforts to receive the necessary financial support to implement the ambitious program that we are planning.

The education and mentoring of a diverse workforce in an inclusive climate allowing students and junior scientists to develop their talents in the most nurturing environment is essential for our community to thrive. There are a few advantages in the RPF experimental environment. The smaller collaborations and the diverse nature of our experimental portfolio create opportunities for people with different aspirations and work styles. Collaborators largely know each other personally. We believe it is possible for those in leadership positions to help set the culture of their experiments, and in a smaller group members can reinforce norms and apply social pressure to each other more effectively.

However, a small collaboration can also easily fall prey to unacceptable behavior if senior members tolerate it without institutional guardrails. A shared goal is to develop a deeper understanding of how to use these advantages while developing common strategies to improve the climate across the various experimental communities. An important tool is the practice of periodic climate surveys. For example, the LHCb collaboration, after performing such a survey, identified critical needs of its early career scientists, and implemented several changes, one of which was the creation of the ECGD (early career and gender diversity) group [140]: the leaders of this group are available for the confidential discussion of concerns from early career scientists or related to gender diversity, and promote awareness of the collaboration of issues that affect this community.

The Frontier needs to address some issues that affect career development for Early Career researchers. For example, researchers in fields such as muon physics tend to be older and leaders tend to stay in positions rather than cycle through as in large experiments such as ATLAS or CMS. It would be facile to simply assert that term limits should be enforced – the collaborations often do not have enough people willing or capable of taking on leadership roles for such rotations to occur regularly. The muon $g-2$ experiment is again an exception; we should study how thisexperiment renewed itself with a younger generation of leaders. The time scale for modern experiments is certainly relevant. It would be useful to examine other "success stories" as well and discern patterns of success and failure.

Lastly, the innovations needed to construct the ambitious instruments that we envision call for multiple connections with industries, especially small industries eager to launch new ambitious projects such as the ones supported by the SBIR grants. Collaborative efforts among scientists at universities and laboratories and industrial partners are keys to innovation that will allow us to both achieve the demanding specifications discussed in the R&D section and examine the applicability of specific technologies to non-HEP applications.

9.6.2 Connections with Other Fields

AMO and Nuclear Physics

The discovery of an electric dipole moment for a fundamental particle such as the electron, or more complicated systems from the proton or neutron to atoms and molecules, would be a clear signal of new physics. Such searches probe mass scales of 10^6 TeV/c^2 or higher, far higher than those directly accessible at any conceivable collider. A coordinated, complementary set of EDM searches in AMO, nuclear, and particle physics experiments could: (a) discriminate among mechanisms that predict the observed matter-antimatter asymmetry and (b) determine whether CP is spontaneously or explicitly broken [141].

Fermion EDMs originate fromnew physics at a high mass scale, requiring new CP-violating phases. Those elementary particle EDMs manifest themselves in bound states at lower energy scales.For protons and neutrons, Lattice QCD is an essential tool in linking the very high-energy origins of EDMs to their manifestation in particles we can observe in the laboratory. Chiral perturbation theory, and nuclear and atomic calculations, continue to even lower-energy scales. Hence theory leads in one direction, but it cannot predict which of the many possibilities occurs in nature; experiment leads upwards from measurements on electrons in the laboratory to BSM physics at inaccessibly high energies.

These low-energy experiments are often studying systems such as nucleons, atoms, and molecules are all fertile ground. Any of these low-energy bound states produce electric fields three-to-four orders of magnitude beyond what can be produced by conventional laboratory methods, making them competitive with the neutron EDM for sensitivity to quark EDMs and $\theta_{\rm QCD}$. The intellectual overlaps are beyond question.

Improvements in AMO techniques have started to rely on creating quantum superpositions analogous to those of Quantum Information Science, certainly a growing topic in particle physics. Advances in QIS might then improve the AMO measurements. Finally, fundamental symmetry tests rely on new quantum sensors: interferometry, optomechanical sensors, and clocks are all cutting-edge tools. Interferometry, in particular, could be used to make an atomic interferometer for gravitational wave detection. Dark matter could also be detected using dual-species interferometers operated with different isotopes.

Another example of overlap, this time with nuclear physics, is the physics of muon capture in muon-to-electron conversion. The muon beams for these experiments are typically ~ 40 MeV/c with only a few MeV of kinetic energy to stop them in thin targets. The muon cascades to a muonic 1s state and can then be converted to an electron in a coherent process with the nucleus. The nuclear wave function is required to calculate the overlap of the two wave functions and then a rate. In addition, the form factor allows differentiation among CLFV models, especially at higher Z materials. The main background driving the beam's time structure is radiative pion capture (RPC): $\pi^- N \to \gamma N'$ where the photon can convert and produce an electron at the signal energy. Unfortunately, the RPC process has not been measured on the likely targets for any proposed muon-to-electron conversion process, and the calculations are decades out-of-date. The RPC rate can be measured *in situ* in Mu2e and Mu2e-II.

Particle production as a result of muon capture ($\approx 60\%$) is also not well-known. However, entire nuclear physics experiments (such as AlCap [142]) have been performed to determine the rates of ejected particles. Their rates and spectra play a significant role in the design of muon-to-electron conversion experiments, since highly-ionizing particles such as protons, ejected during muon capture, can deaden detector elements.

A second mode with $\Delta L = 2$, $\mu^- N(A, Z) \to e^+ N(A, Z-2)$ is related to neutrinoless double-beta decay through the Schechter-Valle "black-box" theorem [143]. Here, the radiative muon capture process $\mu^- N \to \gamma N' \nu_\mu$ is the background, where the photon again converts. The spectrum is poorly known, and nuclear calculations still use the "closure" approximation, which cuts off the spectrum at a kinematic endpoint that may not be appropriate [144]. Furthermore, the process can proceed by either a ground-state to ground-state transition or by a transition to an excited state. There are no modern calculations of the ratio of the ground-to-excited state transitions, and the model of the excited state is a simple giant dipole resonance. While *statistically* the measurements of this mode can be improved by as many orders of magnitude as the improvement in muon-to-electron conversion, this strictly nuclear physics process will be a limitation of the measurement. Many of the same techniques required for $0\nu2\beta$ calculations are applicable here; collaborations between nuclear physicists and high-energy physicists have had only limited success because of the division of the two disciplines. A collaboration between the two fields will be required to make progress.

Finally, experimental and theoretical studies of the properties of the spectrum of hadrons are intimately tied to the underlying theory of QCD, and is therefore also explored in nuclear physics [31, 145].

9.7 Conclusions

The Rare Processes and Precision Measurements Frontier, as expressed in its name, seeks new physics through searches for rare processes and precise measurements. We have identified several common goals that span the Frontier and specific recommendations to achieve our objectives.

- The physics of flavor and generations is a common theme — so much so that we believe it ought to have its own driver. We study flavor through decays of b, c, and the light quarks (RPF1 and

RPF2), measuring precisely the elements of the CKM matrix and performing unitarity tests [7, 8]. Charged lepton flavor violation (CLFV in RPF5), whether in muons, taus, or heavy states (including the Higgs), is another significant focus of the Frontier. All of these groups study rare decays, whether in the b system, CP-violation in the kaon sector, or searches for CLFV. Here we have four specific recommendations:

  - Support the LHCb Phase 2 upgrades and the Belle II program. These experiments perform incisive tests of the Standard Model. Anomalies in the b sector test the unitarity of the CKM matrix along with lepton universality in $B \to K\ell^+\ell^-$ processes. These experiments are not U.S.-based, but we have made significant contributions. We should to continue our role in studying the physics and see the returns on a generation of investment.
  - Embark on a program in muon-based charged lepton flavor violation using the PIP-II accelerator at Fermilab. The intense muon beams made available will surpass any other programs in the world by orders of magnitude and cannot be duplicated. Mu2e was endorsed by the last P5; Mu2e-II is the first step in a staged program that will lead to a systematic study of muon CLFV in all modes, across a wide range of possible sources, at mass scales approaching 10^5 TeV.
  - Strengthen and formalize the R&D in instrumentation that is necessary to carry out this program. Fast timing detectors, precision calorimetry, and low mass trackers are all essential. In addition, the U.S. has an astounding infrastructure in its national laboratories that could drive transformative advances in instrumentation.
  - Pursue strategic R&D in accelerator techniques. The suggested AMF muon program requires the construction of new small rings designed around those experiments [28]. These rings can also enable a world-class dark matter beam-dump experiment. The program also requires high power targeting in a superconducting solenoid, as high as 1 MW; this presents similar problems to those for muon collider targeting. This program could help solve this challenging problem through R&D at intermediate stages. A staged CLFV program from 100 kW moving upwards could help provide a reliable path to a 1 MW-class muon collider target.

- Fundamental symmetry tests are central to our Frontier. The topical group RPF2, examining the physics of light quarks, identified opportunities in K and η/η' rare decays. CP-violation in the kaon system has become an off-shore program, centered at CERN and J-PARC [79, 125]; the U.S. could, if it chose, revive on-shore programs, and the U.S. should strengthen our participation in those efforts. Further insights into fundamental symmetries can be gained through the studies of rare pion decays, for which the interesting PIONEER experimental program has been proposed [81], which also explores lepton universality outside of the b-system. In addition, η, η' factories, such as the upcoming JEF experiment [2] or the proposed REDTOP experiment [4], explore fundamental physics accessible in rare η, η' decays.

- Discovering sources of CP-violation outside the CKM matrix would have profound implications for our studies of leptogenesis and baryogenesis. EDM measurements (RPF3) are ideal for these studies. A proposal for a proton storage ring EDM experiment could reach $10^{-29}e$·cm would result in a three -order of magnitude enhancement for the QCD θ-term EDM over the current limit set by neutron EDM experiments [141]. Discovering sources of CP-violation outside the CKM matrix would have profound implications for our studies of leptogenesis and baryogenesis. EDM measurements (RPF3) are ideal for these studies. A proposal for a proton storage ring EDM experiment could reach $10^{-29}e$·cm would result in a three order of magnitude enhancement for the QCD θ-term EDM over the current limit set by neutron EDM experiments [141].

- The particle nature of dark matter remains one of the greatest mysteries in all of physics. RPF6 has identified a wide range of experiments sensitive to different "portals" between Standard Model and

dark matter. The U.S. should identify a set of such experiments and pursue them aggressively. Such experiments could be performed in hadronic beam dumps, in electron or muon beams, or be added to DUNE. This exciting and rapidly developing area of research is being actively pursued at CERN; the question for the U.S. is whether it will be a leader or cede studies to CERN, as it has in b-physics.

- Baryon and Lepton Number Violation probe fundamental symmetries in particle physics. Our Frontier works in tandem with the large neutrino experiments to search for proton decay or neutrinoless double beta decay; we add efforts in $n\overline{n}$ oscillation and rare $\Delta L = 2$ muon processes.
- Hadron spectroscopy, the driving force of high-energy physics in its early decades, has experienced a renaissance over the past 20 years due to the discovery of scores of new, potentially "exotic" states (tetraquarks, pentaquarks, hybrid mesons, glueballs), as well as the observation of many new "conventional" hadrons. Such research is and will be carried out at LHCb and other LHC experiments, Belle II, BESIII, and GlueX, as well as the approved Electron-Ion Collider, the proposed Super Tau-Charm factory, and other future experiments.
- A robust theory program, supporting both researchers and computing resources, is essential for the success of the experimental activities described in this report.

The Rare and Precision Frontier uses the techniques of many accelerators and experiments to search for new physics and do precision SM tests with diverse and complementary approaches. We have summarized the major themes that emerged during the Snowmass process; the range and power of RPF program are unique and several experiments that we examined encompass the flexibility that enables them to elucidate unexpected observations regardless of where they are found.

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10

Theory Frontier

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Executive Summary

Theory is essential to the field of particle physics, unifying the frontiers and underlying our understanding of the most basic building blocks of Nature. Theory produces transformative science both in connection to *Projects* and in its *own right*. Below we summarize the various indispensible roles theory plays within particle physics.

- Theory is central to the motivation, analysis, and interpretation of experiments.
- Theory lays the foundations for future experiments.
- Theory facilitates our explorations of Nature in regimes that experiments cannot (yet) reach.
- Theory connects particle physics to gravity, cosmology, astrophysics, nuclear physics, condensed matter, atomic, molecular, and optical (AMO) physics, and mathematics.
- Theory extends the boundaries of our understanding of Nature, incorporates new perspectives (such as quantum information), and develops new techniques relevant to experiment.
- Theorists are responsive, pinpointing novel directions based on recent experimental data, proposing future experiments, and developing the precision tools necessary to interpret them, all with the aim of maximizing experimental impact.
- Theorists play a leading role in disseminating new ideas to a wider public and serve as role models for aspiring young scientists.

Together, *fundamental theory, phenomenology* and *computational theory* form a vibrant, balanced and interconnected scientific ecosystem closely aligned with experiment. The past decade has witnessed significant advances across the many facets of the field, with immense promise in the years to come. Here we list some of the highlights.

Fundamental Theory:

- New perturbative and non-perturbative techniques (ranging from the double copy structure of scattering amplitudes to the advent of diverse bootstrap methods) have vastly expanded our knowledge of quantum field theory, in tandem with complementary advances in lattice field theory quantifying non-perturbative properties in theories of interest.
- A deeper understanding of holography and insights from quantum information have breathed new life into the longstanding quest for a complete theory of quantum gravity.
- New effective field theories have facilitated applications of quantum field theory (QFT) to high-energy scattering, Higgs physics, large-scale structure, inflation, dark matter detection, and gravitational waves.

Phenomenology:

- The search for physics beyond the Standard Model has broadened considerably with the advent of novel concepts like neutral naturalness or cosmological selection of the electroweak vacuum.
- Dark matter theory is undergoing a renaissance with the exploration of the full range of allowed dark matter masses, numerous portals to dark sectors, and novel interaction mechanisms. Advances in dark matter phenomenology have gone hand in hand with new proposals for dark matter experiments, often envisioned and implemented by theorists.
- The discovery of gravitational waves has catalyzed rapid progress in precision calculations via scattering amplitudes and inspired the use of gravitational waves to study particle physics inaccessible via planned colliders.
- In precision collider theory the calculation of cross sections to the next-to-next-to-leading order (NNLO) and beyond in QCD has now become possible, unlocking the door to unprecedented tests of the SM. This topic is a prime example where cross-fertilization between phenomenology and fundamental theory has accelerated progress in both areas.
- Precision flavor physics has been the cradle of many of our most powerful effective field theory tools including heavy quark effective theory and soft-collinear effective theory. Taking advantage of the large amount of experimental data, they are now enabling advanced theoretical analyses to obtain constraints on promising beyond the Standard Model (BSM) candidate theories, maximizing the discovery potential of the experiments.
- An explosion of theoretical activity in collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.
- A theory-driven, coordinated program combining nuclear effective theory, lattice QCD, perturbative QCD, and event generation to quantify the multi-scale nuclear cross sections at the needed precision level has been launched, that will allow us to unlock the full potential of the present and future neutrino physics program.

Computational Theory:

- Lattice QCD has become a powerful tool for precision physics, yielding precise SM predictions that reveal surprising new tensions in quark- and lepton-flavor physics. The scope of lattice QCD is undergoing a rapid expansion, promising to provide quantitative access in the coming decade to important new observables, including those involving nucleons and nuclei.
- Innovations in the theory of machine learning (AI/ML), such as the development of (gauge) symmetry equivariant architechtures, driven by theoretical work lattice field theory, collider phenomenology, and other areas, may have transformative impact on computations in high energy theory and beyond.

- Recent dedicated efforts to develop the methods and theoretical foundations for quantum simulations of quantum field theories relevant to high energy theory are already yielding intriguing results on currently available hardware, offering great promise for computations of classically intractable problems in the decades to come.

The US theory community has played a leading role in all of these endeavors, and will sustain its position of international leadership with continued support. To this end,

- The United States and its partners should emphatically support a broad and balanced program of theoretical research covering the entirety of high-energy physics, from fundamental to phenomenological to computational topics, both in connection to experiment and in its own right.
- The theory community is most effective as part of a more balanced HEP program of Projects and Research, as both are essential to the health of the field. Within this balance, support for people is vitally important, as they constitute the primary infrastructure of Research endeavors.
- The effectiveness of the theory community as a part of the broader HEP enterprise is enhanced by targeted bridge-building initiatives that connect theory to experiment, such as the Neutrino Theory Network. Support for ongoing and emerging initiatives will strengthen connections to experiment and sharpen focus on key objectives.
- It is vital to maintain a program in theory (and across HEP) that trains students and junior scientists, providing them with continuing physics opportunities that empower them to contribute to science.
- The success of our endeavors depends on "4π" coverage in identifying and cultivating talent at all career stages. This requires strengthening our commitment to improving diversity, equity, inclusion, and accessibility in the field.

10.1 Introduction

The profound value of theoretical physics is perhaps most apparent in the twin scientific revolutions of the 20th century: relativity and quantum mechanics. At the time of their formulation, neither was thought to have any practical consequences; a century later, they form the foundation of modern technology. Theory lays the groundwork for experiments and technologies of the future. But its value should not be measured exclusively by its potential for future application. Theory addresses our essential human curiosity to understand nature at the deepest level, encompassing not only the actual laws of nature but also the conceivable ones.

The history of the discovery of the Higgs boson and the current and future precision measurements of its properties serve as a perfect illustration of the multiple roles of theory in the particle physics ecosystem. In the early 1960s, the concept of the Higgs mechanism and a Higgs boson was purely theoretical – it was proposed to reconcile a theoretical paradox: how can electroweak symmetry be a basic underlying organizing principle, yet also be broken at the same time. At the time of its invention it seemed impossible to actually detect the Higgs boson; it was fundamental theory making predictions about Nature in regions we could not yet probe. When it became clear in the early 1970s that the Higgs mechanism was indeed likely to underlie the electroweak interactions, theorists started to seriously explore all possible ways of discovering it experimentally, culminating in *The Higgs Hunter's Guide* – an entire book devoted to the various approaches to Higgs detection depending on its detailed properties. These theoretical efforts have motivated and driven a three-decades-long experimental program, first at LEP, then at the Tevatron and the LHC, that famously led to the Higgs discovery in 2012. Theoretical input has strongly influenced the experimental program, even at the level of detector design: the electromagnetic calorimeters in the LHC

experiments were famously designed such that a Higgs decaying to two photons as predicted by theory could be observed and used as a discovery channel. The quest to understand the nature of the Higgs boson by determining its properties at the LHC and at future experiments is also strongly intertwined with cutting-edge theory research. Recent advances in precision collider physics have made calculations of the production cross sections at the needed N^3LO order in perturbative QCD possible. Likewise, the partial decay widths are known through sufficiently high loop order, enabling precise theoretical predictions, when coupled with inputs for the quark masses and strong coupling (α_s) determined from lattice QCD. In this respect, theory is providing key tools necessary to analyze the results of experiments. This one story nicely illustrates all the major roles of theory – from fundamental theoretical concept, to motivating and laying the groundwork for future experiments, to helping analyze and interpret the actual experimental data.

This report summarizes the recent progress and promising future directions in theoretical high-energy physics (HEP) identified within the Theory Frontier of the 2021 Snowmass Process. The goal of the Theory Frontier is to articulate the recent advances and future opportunities in all aspects of theory relevant to HEP, including particle theory, fundamental theory, cosmological and astro-particle theory, and quantum information science. To this end, the Theory Frontier is comprised of eleven interwoven topical groups spanning string theory, quantum gravity, and black holes (TF01 [1]); effective field theory techniques (TF02 [2]); conformal field theory and formal quantum field theory (TF03 [3]); scattering amplitutes (TF04 [4]); lattice gauge theory (TF05 [5]); theory techniques for precision physics (TF06 [6]); collider phenomenology (TF07 [7]); beyond-the-Standard Model model building (TF08 [8]); astro-particle physics and cosmology (TF09 [9]); quantum information science (TF10 [10]); and the theory of neutrino physics (TF11 [11]). The activities of the Theory Frontier complement theory as it appears in the other Snowmass frontiers, and the essential role of theory is further articulated in those frontier summaries.

The central thesis of this report is that theory is a vital and vibrant part of HEP, producing transformative science both in connection to Projects and in its own right. It is essential to the motivation, analysis, and interpretation of experiments; lays the foundations for future experiments; drives of the development and implementation of enabling technologies; and advances our understanding of Nature in regimes that experiments cannot (yet) reach. The theory community in the United States is world-leading, a position that cannot be taken for granted but may be maintained with sustained support and stewardship.

The report itself is organized around three interconnected themes: fundamental theory, phenomenology, and computational theory. The interwoven nature of these themes is illustrated schematically in Fig. 10-1. Fundamental theory is often also referred to as formal theory. It seeks deep understanding of the theoretical and mathematical structures that underlie our modern description of Nature and includes directions which are not (or not yet) directly connected to experimentally testable consequences. Phenomenology explores the connections between theoretical principles and experimental observations to gain deeper insights into the theories realized in Nature. Computational theory seeks to quantitatively test our theoretical descriptions of physical phenomena and gain new insights into fundamental aspects of the underlying theories, through developing and deploying ever more powerful computational methods. It bears emphasizing that these themes are deeply interconnected and effectively inseparable, with developments in each theme strongly influencing the others. While the impact of fundamental theory on phenomenology and computational theory is perhaps the most apparent, developments such as the modern amplitudes program, the revival of the conformal bootstrap, and the development of exact techniques in supersymmetric gauge theories speak to the influence of phenomenology on fundamental theory. Similarly, computational theory has considerably influenced phenomenology by revealing key non-perturbative properties of the Standard Model and its extensions, while new computational tools have enabled rapid progress in diverse aspects of fundamental theory.

Recent developments and promising future directions in each of these three themes have been synthesized from the summary documents produced by each of the eleven topical groups within the Theory Frontier

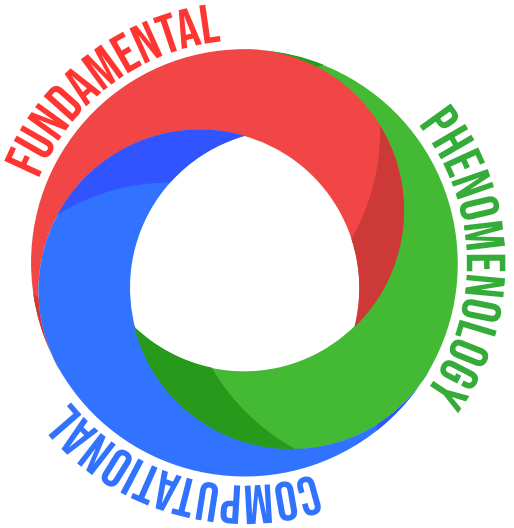

Figure 10-1. *Fundamental theory, phenomenology, and computational theory form a vibrant, balanced, and interconnected scientific ecosystem (represented here as an umbilic torus, whose three-sided cross sections belie its single face) spanned by the eleven topical groups of the Theory Frontier. Image credit: P. Tanedo.*

[1–11]. Given the tightly interwoven nature of progress across the field, each theme combines developments from multiple topical groups, and developments in any one topical group are often reflected in more than one theme. Loosely speaking, the section on fundamental theory primarily covers highlights from TF01, TF02, TF03, TF04, and TF10; the section on phenomenology primarily covers highlights from TF02, TF04, TF06, TF07, TF08, TF09, TF10 and TF11; and the section on computational theory primarily covers highlights from TF05 and TF10 and includes computational developments in other topical groups. This report, and the topical group reports on which it is based, consolidate community input from 150 contributed papers and a dedicated Theory Frontier conference, and reflect refinement by several rounds of community feedback.

10.2 Fundamental theory

It is the great privilege of 21st century physicists to explore the frameworks that arise at the intersection of relativity and quantum mechanics: quantum field theory and quantum gravity. Although textbook methods of quantum field theory have long lent themselves to perturbative expansions at low orders, recent progress has led to new formulations of quantum field theory, new connections between seemingly disparate theories, and the exploration of heretofore-inaccessible regimes. Meanwhile, the decades-long search for a theory that fully combines general relativity and quantum mechanics has been animated by new insights from string theory and quantum information theory. Progress in quantum field theory and quantum gravity has been tightly intertwined by the revelation of holography (the idea that quantum gravitational physics in a region of space is encoded by a quantum field theory living on the boundary of this region) and the surprising double copy relation between scattering amplitudes in gravity and gauge theory. Progress in both areas has contributed to new understanding across wide swathes of physics and mathematics.

10.2.1 Quantum field theory

The historical approach to the union of special relativity and quantum mechanics gave rise to the wildly successful formulation of quantum field theory in terms of path integrals formulated with an explicit measure and Lagrangian. This perspective lends itself to perturbative expansions that underlie much of our current understanding of the Standard Model, but becomes increasingly cumbersome at high orders in perturbation theory and fails entirely in non-perturbative regimes. Both limitations must be overcome in order to completely describe the Standard Model in general, and QCD in particular. Rigorously establishing the existence of Yang-Mills theory and the phenomenon of confinement remains an open question of profound significance. More broadly, the existence of non-Lagrangian QFTs suggests that the historical formulation is essentially incomplete and the space of possible theories remains to be fully explored.

In the past decade, extraordinary progress has been made in developing new non-perturbative approaches to quantum field theory and extending the reach of perturbative ones. Quantum information provides a new perspective on quantum field theory, explored further in Sec. 10.4.2. Symmetries have also played a central role in this progress, including not only familiar spacetime symmetries (such as Lorentz symmetry, conformal symmetry, or superconformal symmetry) and conventional group-based global symmetries, but also more recent generalizations including higher form symmetries, higher group symmetries, subsystem symmetries, and non-invertible symmetries. Although such generalized symmetries have only been discovered quite recently, they appear to be abundantly realized in nature, with considerable relevance to both high energy and condensed matter physics (and even the familiar Standard Model). The implications and applications of generalized symmetries are likely to drive considerable progress in the coming years.

The quantum field theories respecting a given symmetry comprise a deeply interconnected "theory space" populated by both familiar theories and heretofore-unknown ones. The ultimate goals of the modern QFT research program include the characterization of all possible symmetries governing QFTs, the comprehensive mapping of the associated theory spaces, and the construction of their physical observables. Attaining these goals will profoundly expand our understanding of field theories appearing in nature and shed new light on the microscopic physics underlying the Standard Model.

10.2.1.1 Non-perturbative developments

The constraints imposed by symmetries are powerful enough to allow modern "bootstrap" methods to construct observables non-perturbatively and proscribe the space of possible theories. The bootstrap program has been particularly successful in the context of conformal field theories (CFTs), i.e. QFTs with additional symmetry under the conformal group. Such CFTs are ubiquitous, emerging as the long-distance description of many systems in both condensed matter and high energy physics, forming the starting point for the formulation of many QFTs, and featuring prominently in holographic descriptions of quantum gravity via the AdS/CFT correspondence. Recent progress in the conformal boostrap program has been driven by both numerical and analytical advances. On the numerical side, the constraints imposed by conformal symmetry have been reformulated in terms of convex optimization problems. This has allowed world-record computations of critical exponents in physically relevant CFTs such as the 3d Ising model and provided a systematic approach to proscribing the space of consistent CFTs. On the analytic side, diverse Lorentzian methods have led to new solutions of CFTs in various limits, as well as new bounds on event shapes, energy distributions, and S-matrices. Progress in the conformal bootstrap is further synergistic with a growing number of lattice studies of the conformal transition and conformal window in both supersymmetric and non-supersymmetric Yang-Mills theory. Ongoing efforts to merge numerical and analytic approaches are bound to yield considerable progress in the years to come.

Related methods underlie the recent renaissance of the S-matrix bootstrap. Here the imposition of bedrock principles such as analyticity, unitarity, and Lorentz invariance has allowed the space of consistent S-matrices to be mapped out *nonperturbatively* using a variety of optimization methods. Validation of this approach in 2d theories has sparked ongoing efforts in higher-dimensional theories, giving rise to impressive constraints on both pion scattering in 4d and graviton scattering in 10d. These results dovetail with newly-appreciated positivity bounds in effective field theories and with the explosion of perturbative techniques for the computation of S-matrices within the amplitudes program. The recent extension of bootstrap methods to correlation functions in de Sitter space has led to the emergence of a cosmological bootstrap program with far-reaching implications for inflation and early-universe cosmology.

Points in theory space are often related as a function of scale, a generalization of the familiar Wilsonian notion of renormalization group (RG) flow between fixed points. Such flows often proceed from CFTs in the ultraviolet to gapped phases in the infrared, raising the question of whether the physical properties of the IR gapped phase can be reconstructed from the data of the UV CFT and the deforming perturbation. In principle this amounts to diagonalizing the Hamiltonian of the perturbed theory, implemented numerically in the revived framework of Hamiltonian Truncation. Hamiltonian Truncation and related methods have been successfully applied to a range of 2d QFTs, with extensions to 3d and 4d theories underway. Ultimately, this may yield a new nonperturbative scheme for computing the spectrum of 4d QCD starting from a (potentially solvable) UV CFT.

The mapping of supersymmetric theory spaces is especially advanced, particularly for theory spaces governed by (extended) superconformal symmetry. Extensive progress has been made in the classification of both $\mathcal{N} = (2, 0)$ and $\mathcal{N} = (1, 0)$ superconformal field theories (SCFTs) in six dimensions, as well as SCFTs in three, four, and five dimensions obtained by compactification. There are many interesting SCFTs with lesser amounts of supersymmetry in diverse dimensions, related by a rich web of dualities. While the full classification of these theories is out of reach at present, it provides a motivated target for the rapidly-developing bootstrap approaches discussed above. Deformations of these theories are bound to lend new insight into non-supersymmetric theories such as QCD.

10.2.1.2 Perturbative developments and the amplitudes program

Scattering processes are key experimental and theoretical probes of quantum field theories, underlying much of our modern understanding of elementary particles. Scattering amplitudes span all aspects of high-energy physics, ranging from collider physics to mathematical physics to string theory and supergravity, and even recently extending into the realm of gravitational-wave physics. The study of scattering amplitudes (typically, but not exclusively, in perturbation theory) has offered remarkable insight into the structure of quantum field theories and enabled the high-precision theoretical predictions necessary to interpret modern experiments. Recent progress in scattering amplitudes has proceeded through a sort of "virtuous cycle" in which calculating quantities of experimental or theoretical interest fuels new discoveries about the properties of quantum field theories. These discoveries, in turn, enable the development of new computational techniques to generate additional insights.

Scattering amplitudes possess a deep structure that is obscured by traditional Feynman diagrammatic methods. In recent years, considerable progress has been made in revealing this structure, including the description of amplitudes in terms of algebraic curves in twistor space; the development of unitarity-based iterative methods for constructing loop-level amplitudes from tree-level ones; the recursive construction of tree-level amplitudes; the discovery of a hidden "dual conformal" symmetry in planar maximally supersymmetric Yang-Mills theory; the representation of amplitudes in geometric terms (such as the

Amplituhedron); and the revelation that amplitudes exhibit a duality between color and kinematics. These novel descriptions have, in turn, led to greatly improved computational methods.

In the context of fundamental theory, the efficient calculation of scattering amplitudes provides a form of theoretical data that tests new ideas and reveals surprising connections. This has driven significant advances in our understanding of both quantum field theory and quantum gravity. Nowhere is this more apparent than in the study of maximally supersymmetric Yang-Mills (SYM) theory in the planar limit. In some sense the simplest quantum field theory, it provides an ideal testing ground for amplitudes methods and a toy model for theories such as QCD. The perturbative expansion of maximally supersymmetric Yang-Mills is convergent, with ultraviolet-finite scattering amplitudes exhibiting a hidden infinite-dimensional Yangian symmetry. In recent years, this has allowed extraordinary progress in studying its scattering amplitudes at both weak and strong coupling. The virtuous cycle between new methods, new amplitude calculations, and new structures in quantum field theory is bound to yield further advances in the years to come.

10.2.1.3 Effective field theory

Unsurprisingly, the power and generality of quantum field theory leads to considerable mathematical challenges in its application to the real world. Among other sources of complexity, field theories occurring in Nature often feature hierarchically distinct length scales. But locality allows us to disentangle these scales in order to usefully reduce the computational complexity required for a given prediction. In practice, this amounts to finding an appropriate description for the important physics at a given length scale, with the number of free parameters controlled by symmetries and their importance controlled by some form of power counting. This approach is known as effective field theory (EFT).

EFTs are indispensable to the application of quantum field theory in the real world, and many quantum field theories realized by Nature are only understood through the lens of EFT. The modern philosophy of EFT originated in HEP with the study of pion physics, but has since become ubiquitous across many fields of physics. Within HEP, EFT has found use in a dizzying array of contexts ranging from dark matter detection to large-scale structure to high-energy scattering to gravitational waves. EFT reasoning also gives rise to many of the "big questions" surrounding the Standard Model, such as the naturalness puzzles of the electroweak hierarchy problem, the strong CP problem, and the cosmological constant problem. Moreover, the study of EFT itself has yielded new insights into the constraints arising from bedrock principles such as unitarity and causality. Within the past decade, there has been considerable progress in the systematics of effective field theory, as new techniques (augmented by on-shell methods developed in the amplitudes program) have facilitated the explicit construction of EFTs and revealed their underlying simplicity. Growing connections between effective field theory and the amplitudes program are likely to yield further significant advances in the years to come.

Dark matter (DM) detection leverages EFT for both direct and indirect measurements, including systematizing low-energy DM-nuclei interactions and re-summing large logarithms in DM annihilation. In cosmology, EFTs have been employed with great success to study Large Scale Structure (LSS) and inflation. Among other results, EFT calculations have produced state-of-the-art predictions for cosmological parameters extracted from LSS data that are competitive with those from the cosmic microwave background. In models of inflation, EFT techniques have been used to expand analysis strategies and place novel bounds on non-gaussianities.

The role of EFT in collider physics and phenomenology continues to grow. Soft-Collinear Effective Theory (SCET), responsible for greatly improving our understanding of factorization in high-energy scattering, remains central to precision calculations at colliders. The discovery of the Higgs boson at the LHC highlighted the importance of treating the Standard Model as an effective field theory, leading to rapid

developments in the Standard Model EFT (SMEFT) and Higgs EFT (HEFT). These EFTs have transformed the experimental interpretation of Higgs coupling measurements and fuelled considerable exploration (aided in part by the amplitudes program) of their novel field-theoretic properties.

The expansion of EFT techniques into adjacent fields has led to new breakthroughs and produced fruitful feedback back to HEP. For example, EFT approaches in condensed matter physics have shed light on equilibrium phenomena, hydrodynamics, and (non) Fermi liquids, while EFT techniques underlie recent inter-disciplinary study of exotic states of matter known as fractons. A new EFT plays a key role in the burgeoning field of gravitational wave astronomy by organizing the signatures of binary inspirals, with systematic improvements from the amplitudes program.

Beyond its many applications, the framework of effective field theory has been considerably refined in recent years by an improved understanding of the constraints imposed by unitarity and causality, driven in part by developments in the amplitudes program. While the historical approach to EFT (including all effective operators involving the light degrees of freedom, consistent with the symmetries, with arbitrary Wilson coefficients) has been used to great effect, there is a growing appreciation that the apparently-vast space of operator coefficients is sharply proscribed by the existence of a consistent UV completion. Imposing unitarity and causality leads to constraints on the derivative expansions of scattering of amplitudes, often in the form of positivity bounds on Wilson coefficients. This both deepens our understanding of the systematics of EFT and provides powerful guidance to experiments whose results can be framed in terms of EFTs. Rapid progress has been made in the space of the past few years, while the complete exploration of EFT constraints arising from consistent UV completion is a promising target for the years to come.

10.2.2 Quantum gravity

The union of general relativity and quantum mechanics remains one of the main outstanding challenges of theoretical physics. The semiclassical quantization of general relativity is viable as an effective field theory, but breaks down in situations where the spacetime curvature is not small in Planck units. This includes many singularities of profound interest, such as the initial singularity of the universe and singularities in the interior of black holes.

Yet the greatest challenges have a tendency to catalyze the greatest progress. Although radio telescope arrays and gravitational wave observatories have taught us a great deal about the existence and environs of black holes in recent years, at present only a theory of quantum gravity can extend across a black hole's event horizon to characterize the singularity at its center. Thought experiments involving the quantum mechanics of black holes have had transformative impacts on our understanding of quantum gravity and the nature of spacetime.

Semiclassical calculations strongly suggest that a black hole possesses an entropy proportional to its area and evaporates on a timescale proportional to the cube of its mass. These properties lead directly to Hawking's famous information paradox: information about how the black hole was made lies deep in its interior, space-like separated (in the semiclassical picture) from the near-horizon region where evaporation takes place, implying that evaporation destroys this information in contradiction with the unitarity of quantum mechanics. It is by now clear that unitarity cannot be restored by "small corrections" to Hawking's original calculation, requiring us to accept the failure of either quantum mechanics or the semiclassical picture of spacetime. The latter implies that spacetime near black holes – and, by extension, everywhere – must be emergent. Rendering this precise is a central focus of modern research in quantum gravity.

The emergence of spacetime can be made concrete in string theory, where the AdS/CFT correspondence has shed light on the emergence of bulk gravitational spacetime from the field theory description on the boundary. A central breakthrough was the Ryu-Takayanagi proposal, later refined into the quantum extremal surface formula, for computing the von Neumann entropy of a boundary state in terms of bulk quantities. This, in turn, revealed that boundary entanglement is a key element in the emergence of bulk spacetime, encoded most precisely in the revelation that the AdS/CFT correspondence can be understood in this context as a quantum error-correcting code. Most recently, these insights led to the discovery that the "Page curve" – the rise and fall of entanglement entropy entailed by the unitary evolution of an evaporating black hole – can be reliably computed using the quantum extremal surface formula.

Parallel developments have revealed a deep connection between the dynamics of black holes and quantum chaos, namely that simple gravitational calculations serve as probes of chaos in the boundary description. This and related ideas have been explicitly explored in the 2d Sachdev-Ye-Kitaev (SYK) model, thought to be holographically dual to Jackiw-Teitelboim gravity, enabling tests of the chaotic nature of black holes in a solvable regime. Related developments have uncovered connections between computational complexity and the emergence of spacetime, leading to a range of novel insights and ongoing progress. More broadly, the study of quantum chaos in black holes led to a new diagnostic, the out-of-time-order correlator. This can be applied to study chaos in any many-body quantum system, leading to insights ranging from the identification of a characteristic "butterfly velocity" at which chaos propagates, to a general bound on the growth of chaos reminiscent of the "Planckian" bound on many-body transport.

Many open questions remain regarding the emergence of spacetime in the vicinity of black holes. A decade ago, serious obstacles were encountered in realizing a conventional description of the black hole interior in a microscopic theory compatible with the area law for black hole entropy. While some obstacles have been overcome, others persist, and it remains unclear to what extent the interior remains smooth for typical black holes. Relatedly, detailed understanding of the black hole singularity itself is still evolving. Current techniques for analyzing black holes on the gravitational side of the AdS/CFT correspondence remain approximate, leaving boundary observables that cannot be fully accounted for with existing bulk techniques. Addressing these questions requires a deeper formulation of quantum gravity than we currently possess, and comprises a clear goal for the coming decade.

10.2.2.1 Gravity and the amplitudes program

In recent years, it has become clear that deep issues in quantum gravity, including its surprising relation to gauge theories, can be understood through studies of scattering amplitudes. This is exemplified by the discovery and exploration of the double copy, which provides a means to calculate amplitudes in one theory using amplitudes from two technically simpler theories. Most prominently, this allows gravity scattering amplitudes to be constructed from pairs of gauge theory amplitudes. Such relations were originally discovered in string theory and subsequently greatly expanded by the discovery of a duality between color and kinematics, in which gravity amplitudes are generated by gauge theory amplitudes from the replacement of color factors with kinematic ones. This duality relates not only gravity and gauge theories, but also a wider variety of familiar field and string theories. Although first identified in perturbative scattering amplitudes, the double copy is being systematically extended to classical solutions as well. In the coming years, we can expect considerable development of the double copy in many directions.

Amplitudes methods have also contributed greatly to the understanding of the perturbative S-matrix in string theory. Recent developments have pushed string perturbation theory to three loops, leading to a number of non-trivial results. Future targets include circumventing technical obstacles to higher-loop string amplitudes and exploring the rich mathematical structure of Feynman integrals associated with

K3 or Calabi-Yau geometries. Advances in string perturbation theory have enabled qualitatively new developments such as the Cachazo-He-Yuan (CHY) formalism and ambitwistor string models. The former expresses field theory amplitudes as integrals over the string worldsheet localized at the points which satisfy scattering equations; these integrals are built from simple building blocks and manifest connections between various field theories, including color-kinematics duality. The ambitwistor string expresses the same field theory amplitudes as the worldsheet correlators of ambitwistor strings, drawing fascinating new connections between string and field theory amplitudes. The existence of such novel descriptions of field theory scattering amplitudes in terms of string theory points to new underlying principles in quantum field theories.

10.2.2.2 Particle physics and cosmology

In addition to deepening our understanding of quantum gravity itself, recent progress has also had far-reaching implications for particle physics and cosmology. Although the gravity is famously the one force not contained within the Standard Model, the Standard Model is ultimately embedded within a theory of quantum gravity. This motivates obtaining the Standard Model from a complete microscopic description such as string theory, in the process potentially addressing many of its outstanding mysteries. Progress has been most rapid in obtaining Standard Model-like theories with some degree of supersymmetry, inasmuch as this simplifies the construction of stable compactifications to four dimensions. In recent years, considerable progress has been made in the non-perturbative "F-theory" description of Type IIB string theory, in which supersymmetric Standard Model-like theories are obtained by engineering appropriate singularities in Calabi-Yau geometries. The classification of Standard Model-like theories translates into a concrete (albeit highly non-trivial) problem in algebraic geometry. Augmented by machine learning and other numerical developments, ongoing efforts are beginning to shed light on typical properties of these realistic theories, including the types of gauge groups, spectrum of charged states, and number of generations. A more ambitious goal is to obtain realistic models with supersymmetry broken at higher scales (such as the compactification scale or the string scale). This introduces new technical challenges, most notably the stability of scalar fields in the low-energy spectrum. Fruitful investigation is underway, and the construction of theories without low-energy supersymmetry is a compelling target for the coming decade.

Quantum gravity and cosmology are deeply intertwined. A fully quantum theory of gravity is necessary to understand the initial singularity of the universe, while the subsequent expansion of spacetime leaves imprints of short-distance physics visible on cosmological scales. Models of quantum gravity can inform both the early inflationary epoch and the current dark energy-dominated era. In string theory, the value of the cosmological constant depends on both the shape of the internal dimensions and the presence of additional extended objects such as branes and fluxes. Extensive progress has been made in constructing string configurations with positive values of the cosmological constant, fueling ongoing dialogue aimed at bringing these constructions under complete theoretical control.

A question of great experimental and theoretical interest is whether string theory or other frameworks for quantum gravity can produce inflationary models matching current and future observations. Of particular interest are predictions for the tensor-to-scalar ratio r, which is sensitive to the total displacement of the inflaton as it rolls down its potential and will be constrained at the level of $r \leq 10^{-3}$ by future experiments. Present constraints already exclude a range of effective field theories with large values of r, and it is a pressing question whether – and where – there is a theoretical upper bound on r in complete models of quantum gravity. Microscopic models of inflation lead to a range of potentially observable features, including distinctive non-gaussian features in the cosmic microwave background or a reduced sound speed during inflation. A more complete theory of quantum cosmology is also essential to resolving the puzzles of "eternal inflation" that arise in many inflationary models. Eternal inflation in the semiclassical approximation gives

rise to a vast, inhomogeneous universe where conventional notions of probability lead to bizarre paradoxes, the resolution of which is likely to be found in the theory of quantum gravity.

10.2.2.3 Gravity and effective field theory

The novel properties of a quantum theory of gravity provide new challenges and opportunities for effective field theory, both for gravitational EFTs and non-gravitational EFTs embedded in a theory of quantum gravity.

Due to the presence of a massless graviton in the spectrum, gravitational EFTs have long resisted the development of positivity bounds akin to those arising in their non-gravitational relatives. However, rapid progress over the past few years has overcome many of the obstructions, leading to the first bounds on the operator coefficients of the leading corrections to Einstein gravity. In a complementary direction, CFT data has recently been used to constrain gravitational EFTs in AdS with holographic duals, including the establishment of rigorous bounds using the conformal bootstrap.

In addition to the bounds on effective field theories arising from unitarity and causality, surprising constraints may also arise from consistent embedding in a theory of quantum gravity. These constraints are collected under the umbrella of what is now known as the "Swampland program." Since a general definition of quantum gravity (and the universal properties of consistent theories coupled to it) are not rigorously established, these constraints are conjectural. However, in many cases they are supported by a diverse spectrum of evidence from perturbative string theory, semiclassical gravity, holography, and other sources. While some Swampland arguments can be related to positivity bounds of the types described above, in other cases they lead to entirely new constraints on EFTs. More broadly, phenomena such as black hole formation can lead to novel UV/IR infrared mixing phenomena that significantly generalize the standard notion of effective field theory and merit further study. Insofar as the Standard Model can be seen as an effective field theory coupled to gravity, these constraints and considerations provide a new avenue for addressing many of the Standard Model's long-standing puzzles.

10.2.3 Broader implications for mathematics and physics

In the course of answering questions in high-energy physics, fundamental theory uncovers both new mathematical structures and new approaches to problems in far-flung fields.

From classical mechanics to general relativity, fundamental theories of physics have evolved hand-in-hand with mathematics. This is no less true for modern approaches to quantum field theory and quantum gravity. Recent implications for both geometric and algebraic aspects of mathematics have included direct connections between the classification of SCFTs and the theory of canonical singularities in algebraic geometry; wrapped brane states in string theory and the mathematics of enumerative invariants; and 2d rational CFTs and their associated vertex operator algebras. Connections between QFT, string theory, and number theory are exemplified by the "moonshine program" which has uncovered striking relations between modular forms and the representations of finite groups, disparate areas of mathematics that have been connected through the physics of 2d CFTs, vertex operator algebras, and associated constructions in string theory. Further relations between number theory, algebraic geometry, and quantum field theory are emerging from the geometric Langlands program. Recent work on perturbative scattering amplitudes also revealed deep connections to active areas of work in mathematics. This ranges from the theory of special functions, polylogarithms, elliptic functions, calculations of multi-dimensional integrals, and modern use of

differential equations to intriguing links to combinatorics, algebraic geometry, Grassmannians and positive geometries. Exploring the field-theoretic implications of new mathematical structures, and vice versa, is bound to be fruitful for years to come.

Insofar as the AdS/CFT correspondence relates strongly coupled quantum systems to gravity, it can be used to understand a range of strongly-coupled interacting systems using straightforward computations on the gravity side. This has produced a number of insights in many-body physics including bounds on transport, bounds on chaos, and hydrodynamics with anomalies. In many cases, gravitational calculations inspired conjectures that were later proven in general, making the gravity side of the AdS/CFT correspondence a valuable laboratory for many-body physics. Strange metals (relevant for high-temperature superconductivity) have proven amenable to study using near-extremal black holes with a suitable horizon geometry, while models on the condensed matter side (such as the SYK model mentioned earlier) have improved our understanding of near-extremal black holes. Finally, qualitative similarities between the deconfined phase of QCD and maximally supersymmetric gauge theory at finite temperature have made the AdS/CFT correspondence relevant to the study of the quark-gluon plasma, leading to progress on real-time, out-of-equibrium problems including transport properties and jet quenching.

Progress in quantum gravity has also driven progress in classical gravity. A good example is the recent use of quantum scattering amplitudes for pushing the state of the art in precision calculations of classical gravitational waves. Insights arising from the AdS/CFT correspondence include the discovery of the "fluid-gravity correspondence" connecting Einstein's equations to the Navier-Stokes equations of hydrodynamics, exotic new solutions to Einstein's equations, and astrophysical signatures of near-extremal Kerr black holes, as well as the derivation of the Penrose inequality (a proxy for cosmic censorship). Connections between soft theorems, the memory effect, and the Bondi, van der Burg, Metzner, and Sachs (BMS) group of asymptotic symmetries has been discovered, motivating new efforts to develop a theory of flat-space holography. Resonances between classical and quantum gravity are bound to grow in the coming years, with progress flowing in both directions.

10.3 Phenomenology

Particle phenomenology provides the connection between fundamental theory and the physical description of the real world, testable by experiments. Phenomenology has many crucial aspects essential for a successful experimental program in particle physics:

- Phenomenology helps formulating the physics goals of particle experiments, identifying promising new avenues for experiments, and also in interpreting their results, ideally by synthesizing them into a coherent model.
- Phenomenology provides the tools to perform the precision calculations necessary to compare the experimental results to theory predictions.
- Phenomenology helps providing many of the tools used for successfully analyzing and interpreting the results of the experiments. It often identifies signals requiring novel analysis techniques.

Along these lines we distinguish the various aspects of phenomenology as model building, precision physics and collider phenomenology. We discuss cosmology and astrophysics as well as neutrino physics in separate subsections to highlight aspects of theory specific to these topics.

Many aspects of particle phenomenology play a direct role in formulating the Projects of the next decade, and particle phenomenologists are actively contributing to or leading these studies. The role of the Theory

Frontier is to highlight the important aspects of phenomenology that are providing more general tools or long term goals, which will be likely essential for the long-term success of the experimental program, but are not yet directly contributing to the Project-based frontiers. The direct contributions by particle phenomenologists will be highlighted in the Frontier Reports of the Energy, Cosmic, Rare and Precision, Computational and Neutrino Frontiers.

10.3.1 Model building

There are several clues indicating the need for physics beyond the Standard Model: the origin of neutrino masses, the quark and lepton flavor structure, the absence of CP violation in the strong sector, the coexistence of the weak and gravitational scales, the origin of dark matter and dark energy responsible for the acceleration of the universe. Model building attempts to synthesize these clues into the next set of principles which determine the laws of physics at the shortest distance scales. While all BSM models approximately reproduce the SM at low energies, they introduce a plethora of testable ideas using a broad range of theoretical approaches and techniques. Many of these have led to new experimental search strategies at existing experiments, as well as to formations of wholly new experimental programs, often co-led by theorists.

10.3.1.1 Naturalness

Naturalness has been one of the guiding principles for BSM model building over the past three decades. These naturalness puzzles arise in trying to understand why a dimensionless number is much smaller than $\mathcal{O}(1)$. These include the electroweak hierarchy problem (m_h^2/M_{Planck}^2), the cosmological constant problem ($\rho_\Lambda/M_{Planck}^4$), the strong CP problem (θ_{QCD}) and the flavor problem (y_f).

The traditional approaches to the electroweak hierarchy problem are to extend the SM around the weak scale with new particles that have a built-in mechanism for eliminating further sensitivity to high mass scales. Generically these would involve new colored particles, in particular top partners. The canonical example is supersymmetry, which would predict scalar tops, or compositeness/warped extra dimensions which predicts fermionic top partners. These particles have been extensively searched for at the LHC without success, pushing the scale of such new particles beyond 1 TeV, leading to the reintroduction of some of the hierarchies ("little hierarchy") the models were intending to explain. The status of weak scale supersymmetry is far from settled. In its original incarnation, in light of the LHC data, the MSSM now has to exist in moderately fine-tuned regions of the parameter space, but it is also possible that the superpartners most easily accessible are beyond the reach of the LHC such as in split SUSY, or that the structure of weak scale SUSY is qualitatively different from that of the MSSM. The search for warped extra dimensions/compositeness has been one of the driving forces of the experimental program over the past decade, leading to novel search strategies that were often applicable to other BSM scenarios as well. As for SUSY, the simplest models now have to live in moderately tuned regions, but again qualitatively different implementations are still possible and are continuously being explored and tested.

One elegant way around the non-discovery of top-partners in BSM models explaining the electroweak hierarchy is Neutral Naturalness, where a new symmetry relates the SM quarks to colorless particles. The most well-known of these is the Twin Higgs model, and a generic feature is the emergence of multiple sectors related by some discrete symmetry. These models typically require UV completions with colored states at the multi-TeV scale, motivating future high-energy colliders. The Higgs often acquires new or exotic decay modes, proportional to the SM Higgs to the twin Higgs VEV v/f, which is also directly proportional to

the tuning in the model. The exact implementation of neutral naturalness will significantly influence the resulting phenomenology. Particularly interesting is the case where the twin confining sector has no light quarks, leading to a "quirky phenomenology", where heavy quarks behave as if connected by a string with constant tension, giving rise to a shower of glueballs, some of which have displaced decays to SM states. Neutral naturalness is expected to be one of the dominant paradigms driving experiment and theory over the next decade.

An important new direction that emerged over the past decade is the cosmological selection of the electroweak vacuum, which was inspired by similar attempts at selecting the cosmological constant or θ_{QCD}. The best known example is the relaxion, where an axion-like field (the relaxion) traverses large values in field space, and provides a rolling Higgs mass in addition to the usual axion-like coupling to $G\tilde{G}$ of QCD. Once the Higgs develops a VEV wiggles will develop for the relaxion due to the usual QCD-like contribution to the axion potential, which will stop the rolling of the relaxion. Building a realistic model is challenging, in particular it is very hard to protect the shift symmetry of the axion over trans-Planckian field excursions. Another popular model of cosmological selection is called N-Naturalness, containing a very large number of copies of the SM, but only those with a small Higgs mass will acquire significant energy densities after reheating. Cosmic selection models are expected to be among the dominant topics in the near future, stimulating new experimental searches and predicting novel signals.

The most famous approach to the strong CP problem is the QCD axion, which dynamically adjusts its VEV to cancel the strong CP phase. Search for the axion has motivated a thriving experimental program with lots of synergy between theory and experiment, which in turn has rejuvenated axion model building, where the properties of the QCD axion are varied away from the naive expectations. One challenge axions are facing is the quality problem: to ensure there be no sources of explicit breaking of the shift symmetry other than QCD itself, which has inspired another branch of axion model building. Axions can also play a role in large-field inflationary models. Axion physics will likely keep attracting enormous attention and lead to new experimental setups for axion searches.

10.3.1.2 Dark matter

The existence of dark matter (DM) is one of the most compelling pieces of evidence for physics beyond the Standard Model. Dark matter has driven many of the developments over the past decade in particle theory, particle astrophysics and cosmology. It has also been an area of major focus for model building, with null results at large direct detection experiments driving increasing efforts to explore the vast theory space for dark matter. Insofar as dark matter model-building is inextricably linked with theory-led proposals for dark matter detection, the main discussion of the topic is reserved for Sec. 10.3.4.

10.3.1.3 Baryogenesis

The observed baryon-antibaryon asymmetry in our Universe calls for a mechanism of baryogenesis after the reheating post-inflation. Any such mechanism has to satisfy the three Sakharov conditions of baryon number violation, C and CP violation, and departure from equilibrium. While the SM nominally satisfies all three, the CP violation due to the phase in the quark mixing matrix (CKM) appears to be too weak, and no processes in the SM go out of equilibrium in the early Universe, necessitating BSM physics for baryogenesis. The best-known model is leptogenesis, where a leptonic asymmetry generated by right handed neutrino decays is transferred to a baryon asymmetry via electroweak sphalerons. Another option is electroweak baryogenesis, happening during the electroweak phase transition. There have been numerous novel models

introduced over the past decade, resulting in many experimentally testable models, since they involve low scales. This topic is expected to keep attracting ever growing attention.

10.3.1.4 Flavor and neutrino models

Flavor violating processes, in particular those involving flavor-changing neutral currents (FCNCs), have exquisite sensitivity to new sources of flavor and CP violation, due to the special flavor structure of the SM. The origin of this flavor structure including the hierarchical quark and lepton masses, the hierarchical CKM matrix, and the non-hierarchical neutrino mixing matrix (PMNS) is referred to as the SM flavor puzzle. Various classes of models exist to solve it, including horizontal flavor symmetries, warped extra dimension/partial compositeness, and radiative fermion masses. Quark FCNCs can often indirectly explore mass scales well beyond the reach of current colliders, while charged lepton FCNCs and electric dipole moments are powerful null tests of the SM. Over the last several years a number of flavor anomalies have emerged creating considerable excitement in the community. These include some decay modes of the B meson as well as the anomalous magnetic moment of the muon. If these anomalies survive they would have transformative impact on particle physics, establishing a new mass scale, providing a new target for direct exploration at future colliders.

10.3.2 Precision physics

Theoretical techniques for precision physics are the backbone of a successful program in particle physics. They are necessary for determinations of fundamental parameters of the Standard Model (SM) to unprecedented precision and probe beyond SM (BSM) physics to very high scales. Potential dark matter candidates, explanations of the hierarchy puzzle, and many other discoveries could be made, even if the mechanisms underlying them are at the tens of TeV scale or even beyond. Here we review some of the recent advances and expected future prospects for precision physics appearing both for collider phenomenology as well as for flavor physics.

10.3.2.1 Precision collider phenomenology

The first step is the calculation of the perturbative hard scattering cross sections to the requisite order in perturbation theory. There has been tremendous recent progress on this front, mostly due to a cross-fertilization between formal/mathematical developments in understanding the properties of multi-loop amplitudes and to a clever and efficient reorganization of different contributions into infrared (IR) safe observables up to next-to-next- to-leading order (NNLO). As a result, the current standard for cross section predictions at the LHC is next-to-next-to-leading order (NNLO) in perturbative QCD for $2 \to 2$ scattering processes without internal mass scales in the contributing loops. For a host of processes the $\mathrm{N^3LO}$ corrections in perturbative QCD are also available. The challenge facing the theory community is to extend these computations of hard scattering cross sections at $\mathrm{N^3LO}$ to include jet processes and more differential observables. Numerous issues must be addressed to achieve this challenge: the computation of the relevant three-loop integrals, understanding the basis of functions needed to describe these corrections, and the extension of infrared subtraction schemes to handle triply-unresolved limits. Moreover, higher-order electroweak (EW) corrections become increasingly important with improved precision of LHC analyses. NLO EW corrections for $2 \to n$ processes can now be carried out in a mostly automated fashion (for n up to 8). A few results are already available for NNLO mixed EW-QCD corrections, while only one NNLO

EW result (for the leading Z-resonance contribution to Drell-Yan production) has been obtained so far. The computation of higher-order EW corrections involves unique challenges due to the appearance of many masses in the loop integrals, which impedes analytical solutions to the latter.

While computations of the hard scattering cross section at fixed orders in perturbation theory are sufficient for many applications, this is not the case for all situations. In multi-scale problems, when one mass scale is very different than the others, large logarithms of the scale ratios can appear, and fixed-order perturbation theory doesn't converge. To get a reliable prediction one must resum these large logarithms to all orders. There have been many important new devlopments on this front, including resummation beyond leading power, the joint resummation of different classes of logarithms relevant for jets and their substructure, small-x resummation in the high-energy regime, and the QCD fragmentation processes.

All hadron collider predictions require understanding of the parton distribution functions (PDFs) that describe how to take a parton of a given momentum fraction from a hadron. Although there has been significant recent activity in attempting to calculate PDFs using lattice techniques, for the practical purpose of predicting collider physics cross sections they are extracted from experimental data. This leads to the following three issues that must be addressed in order to have PDFs computed to the needed level for LHC and future collider predictions: the perturbative DGLAP (Dokshitzer–Gribov–Lipatov–Altarelli–Parisi) evolution of the PDFs must be calculated to match the precision of the hard scattering cross section; the hard scattering cross sections from which the PDFs are extracted from data must be known to NNLO or N^{3}LO depending on the desired accuracy; the experimental data used in the extraction must have small enough uncertainties to match the above theoretical uncertainties, and must also be sufficiently broad enough to fix the functional dependencies of all PDFs on x.

Both fixed-order and resummed predictions describe collider observables that are inclusive, or differential in a few variables. They are formulated in terms of partonic degrees of freedom. Parton-shower event generators are needed to provide a closer realization of the actual events in terms of hadronic degrees of freedom measured in experiment. Parton-shower event generators such as HERWIG, PYTHIA and SHERPA are heavily used by experimental collaborations in their analyses and form an indispensable tool for understanding events at high-energy colliders. There have been numerous theoretical improvements in parton showers over the past years, resulting in programs more faithful to the underlying QCD theory. Future precision measurements of the Higgs and electroweak sector at planned Higgs factories will require N^{3}LO and possibly even N^{4}LO EW and mixed EW-QCD corrections calling for new innovative techniques that combine analytical and numerical methods, while planned multi-TeV proton-proton and muon colliders will require novel tools for the resummation of multiple emission of massive gauge and Higgs bosons (EW parton distribution functions, EW parton showers, etc.) and energy-enhanced radiative corrections.

The SM effective field theory framework will inevitably be the framework in which future indirect searches for physics beyond the SM are interpreted. The SMEFT Lagrangian is constructed containing only the SM degrees of freedom, and assuming that all operators satisfy the SM gauge symmetries. This leads to a result that differs from the SM Lagrangian by a series of higher-dimensional operators suppressed by a high energy scale Λ at which the EFT description breaks down. Predictions in this EFT require not only expansions in the usual SM couplings, but also in the ratios v/Λ and E/Λ, where v denotes the Higgs vev and E the characteristic energy scale of the experimental processes under consideration. As experimental precision increases, and as E increases, higher operator powers must be considered for reliable predictions. An essential step for interpretation of future high-precision HL-LHC data within SMEFT is the extension of predictions beyond the leading dimension-6 order. It has been demonstrated that constraints derived assuming only dimension-6 operators can be unstable against the inclusion of dimension-8 effects. It has also been shown that dimension-8 terms are needed to faithfully reproduce the underlying UV theory in some cases. Significant effort must be devoted to understanding the impact of dimension-8 and higher-order effects.

10.3.2.2 Precision Flavor Physics

A key feature of flavor physics — the study of interactions that distinguish between the three generations — is the plethora of observables that probe very high mass scales, well beyond the center-of-mass energy of the LHC or any planned future colliders. This high mass-scale sensitivity arises because the SM flavor structure implies strong suppressions of flavor-changing neutral-current processes (by the GIM mechanism, loop factors, and CKM elements). The ongoing and planned flavor experiments provide essential constraints and complementary information on BSM models. The measurements of dozens of CP-violating and FCNC processes at e^+e^- colliders and at the LHC are consistent with the SM predictions, with ever-increasing precision (with a few exceptions; see the discussion of flavor anomalies below), leading to the "new physics flavor problem", which is the tension between the hierarchy puzzle motivating BSM physics near the electroweak scale, and the high scale that is seemingly required to suppress BSM contributions to flavor-changing processes. The bound on the scale of flavor violating dimension-6 operators reaches above 10^5 TeV for the most sensitive observables like ϵ_K and the electron EDM, with the greatest improvements over the next decades expected in $\mu \to e$ conversion ($\mu N \to eN$) and EDM experiments. These bounds also have important impact on model building: for SUSY one needs to augment the model with some mechanism to suppress the SUSY flavor violating contributions, for example via degeneracy, quark-squark alignment, heavy (3rd generation) squarks, Dirac gauginos with an extra R symmetry, or split SUSY. Warped extra dimensions have a built-in RS-GIM mechanism that naturally reduces FCNC close to the experimental bounds. A widely applied concept in BSM model building is minimal flavor violation (MFV), which posits that BSM sources of the breaking of the global $[U(3)]^5$ symmetry of the SM are proportional to the same Yukawa couplings, which often reduces FCNCs to lie within the bounds.

The richness of B physics and the large b-quark mass enable many complementary tests of the SM, and have been a driving force to develop new perturbative multi-loop and nonperturbative effective field theory techniques since the 1980s. For example, a precise determination of $B \to X_s\gamma$ makes it essential to consistently combine fixed-order perturbative calculations, resummations of large logs (of various kinds) in endpoint regions, and nonperturbative ingredients, each of which has grown into significant areas of research. The desire for (hadronic) model-independent understanding of semileptonic B-meson decays led to the development of heavy quark effective theory (HQET), which was instrumental in the development of many other effective field theories including nonrelativistic general relativity (NRGR). Studying inclusive $B \to Xl\nu$ decays led to the development of the heavy quark expansion, which has served as a model for other operator product expansions. The soft-collinear effective theory was developed initially motivated by summing Sudakov logs in $B \to X_s\gamma$ in an effective theory framework. SCET has also become part of the standard theory tool-kit for higher order collider physics calculations. In the area of multi-loop calculations, flavor physics also instigated developments of numerous technical aspects. This decade Belle-II is expected to produce new data for inclusive B-meson decays such as $B \to X_s\gamma$ and $B \to X\ell\nu$. To match this experimental development, new theoretical work that utilizes HQET and SCET is needed. It will combine existing and new perturbative calculations as well as better control of non-perturbative inputs.

Over the past five years several anomalies have also emerged from the flavor experiments, that could potentially point to new physics BSM if these anomalies persist after further experiments and more precise theoretical determination. Most prominent among the anomalies are the hints for lepton flavor universality violation (LFUV) in two set of processes. One is in neutral current $b \to sl^+l^-$ transitions, $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$, where the most recent LHCb measurement shows a 3.1σ deviation from the SM, while the other is in the charged current $b \to cl\nu$ transition, $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}l\nu)$, where $l = e, \mu$. In this case the significance for the deviation from the SM is quoted as 3.1σ to 3.6σ, depending on the treatment of correlations. In both of these cases, the present data hint at about $15 - 20\%$ corrections to the SM predictions. In the SM predictions of the $R_{K^{(*)}}$ ratios, contributions from form factors and non-factorizable effects largely cancel, yielding theoretical predictions

with negligibly small uncertainties. Hence more precise measurements of $R_{K^{(*)}}$ could break the SM (if the central values stay unchanged). SM predictions of the $R(D^{(*)})$ ratios, on the other hand, depend on the underlying form factors, which must be known with sufficient precision in order to assess the tensions between the SM and experiment. Lattice-QCD results for semileptonic B-meson decay form factors are currently available with complete error budgets at a commensurate precision level to experiment, also yielding reliable determinations of CKM elements from experimental measurements of differential decay rates. To take advantage of more precise experimental measurements, there are ongoing efforts to reduce the uncertainties in lattice-QCD form factor calculations in tandem (see Sec. 10.4.1). With the expected improvements in experimental precision, a common challenge in both $b \to ql\nu$ and $b \to qll$ mediated decays is that going forward, the role of electromagnetic corrections needs to be better understood, and the related uncertainties assessed.

To fully utilize the next generation of measurements, a better theoretical understanding of nonleptonic decays is much desired. To date, most CP violation measurements have been performed for such decays, as they not only allow measurements of the CKM unitarity triangle angles, but also provide numerous probes of CP-violating BSM interactions. A promising recent theoretical development extends factorization of nonleptonic decays to order Λ_{QCD}/m_b, with regularized endpoint divergences. This can lead to a better theoretical understanding and control of nonleptonic decays. There is also active ongoing research on studying CP violation in charm and kaon decays as probes of the SM and new physics.

10.3.3 Collider phenomenology

Collider phenomenology is a highly active theoretical area that connects in crucial ways to the experimental energy and precision frontier programs. It is an essential interface between the theoretical and experimental high-energy physics communities, serving various roles: from connecting formal investigations to experiments, such as providing guidance on the exploration of the physics possibilities, to supporting the experimental community with the essential tools to simulate and interpret data, bringing information back to the theory community. Below we review some of the most exciting recent developments as well as the directions with most promise for the coming decade.

10.3.3.1 Collider observables

At the heart of collider phenomenology is choosing and defining observables. While cross section is the most basic observable, it doesn't contain much information about the microscopic physics. By making more differential measurements, one gains access to different regions of phase space and rarer processes, and therefore increases the information. The design of observables also plays a key role in separating out known background processes from the signals of interest. Often it is important to develop observables that expose kinematic features, leading to the development of specialized observables which are expected to play an important role in studying new physics scenarios with multi-body final states. An area of rapid development over the past decade has been the field of jet substructure: variables that are designed for tagging jets either as arising from SM partons, or exotic jets arising from new physics scenarios. A newly emerging and very promising field is the study of multi-point correlators, where each event contributes to several entries of the histogram, weighted by the product of particle energies. Because of this weighting, energy correlators are less sensitive to soft physics and can be calculated accurately. In addition the scaling behavior of these correlators can often be deduced from the conformal limit. We expect these novel theory driven observables to play a major role in the collider physics of the next decade. Another new method revolutionizing the subject of collider observables is using machine-learning (ML) based observables, where data itself is used to

define the observables. One important new insight is that ML can incorporate symmetry group equivariance, such that these methods respect the know theoretical structures of collider physics, such as permutation and Lorentz symmetries. An important example of unsupervised ML is optimal transport, which is based on the relationship between pairs of collider events, rather than treating them independently. This method led to strategies for quantifying the dimension of collider events, and to new observables like event isotropy. Another emerging direction is the use of quantum algorithms for collider physics. It has been successfully used to compute collider observables; whether they will eventually lead to a dramatic computational gains depends on whether efficient ways for encoding classical data in quantum form can be found.

10.3.3.2 Precision calculations

Once an observable has been defined, one needs to calculate the distribution accurately enough in the Standard Model to match current and expected precision from experimental measurements. In addition, predictions in specific BSM scenarios or in effective field theories are needed to establish the sensitivity to new physics as well as to devise optimal search strategies. We are reviewing the recent progress and future prospects of the precision collider physics calculations in Sec. 10.3.2.

10.3.3.3 Event generators

Very few theoretical calculations can be performed analytically, so Monte Carlo event generators are the workhorse strategy to make theoretical predictions which can most directly be compared to experimental data. As experimental methods become more sophisticated, theoretical innovation in multi-purpose event generators becomes increasingly important. In precision collider measurements, a significant (or even dominating) source of uncertainties of experimental analyses is often associated with event generators. A large part of recent development activities in Monte Carlo event generators focuses on extending their applicability and reducing their uncertainties. Event generation at present and future colliders feature many common ingredients: higher-order QCD and EW corrections, factorization theorems and parton evolution, resummation of QCD and QED effects, hadronization, and initial and final-state modeling. In addition to the physics components, there are also computing elements, such as interfaces to external tools for analysis, handling of tuning and systematics, and the need for improved computational efficiency. In addition to being a theoretical challenge, the increase in precision is becoming a computational challenge, partly because the complexity of higher-order predictions for multi-particle final states increases exponentially with the order and number of final states, and partly because the expected increase in collected data calls for the production of very large sets of fully simulated events. One way of address the ballooning computational cost of event generators is through machine-learning-based generators. Modern machine learning is driving recent progress in event generation, simulation, and inference for high-energy colliders.

10.3.3.4 Interpretation tools

Interpretation lies at the intersection of theoretical and experimental collider physics, which requires dialogue between communities, and collider phenomenology is a language to facilitate that dialogue. Model-specific searches for new physics are a well-understood strategy for data interpretation, but there is increasing interest in anomaly detection for collider physics. A quasi-model-independent approach to interpretation is the use of effective field theories. If the impact of heavy new physics states can be captured by contact interactions involving Standard Model fields, then one can do a systematic expansion order by order in power counting, leading to the Standard Model effective field theory. A key challenge facing collider physics is

data and analysis preservation. To maximize the scientific potential of archival collider data sets, theoretical physicists should actively participate in proposing and stress-testing archival data strategies.

10.3.3.5 Search strategies

There is a huge range of possible scenarios beyond the Standard Model, and each scenario requires different observables to maximize signal acceptance and minimize background contamination. Model-specific searches remain the gold standard for the field, since they provide a well-defined statistical framework for setting limits (or announcing a discovery). Theorists have made significant contributions to proposals of novel measurements of the newly discovered 125 GeV Higgs boson, including for example exotic Higgs decays, measurement of the Higgs width and the Higgs coupling to charm. Model agnostic searches, though, are gaining traction, as it becomes increasingly possible to automate certain aspects of the search process. The most heavily studied examples include the cascade decay signature appearing in models with an extended Higgs sector, composite Higgs models with vector-like fermions or warped extra dimension models with Kaluza-Klein (KK) modes. Heavy particles produced at high-energy colliders could lead to boosted objects with interesting substructure. The study of dark sectors has been a subject of interest in recent years, including dark showers, portal matter, and multi-field scenarios. The field of detecting long lived particles (LLPs) has also undergone a major revolution: besides new analysis techniques at existing experiments several auxiliary detectors like FASER, Mathusla or CODEX-b have been proposed and co-led by theorists, some of which are already under construction. Low-mass scalars are a key target for current and future colliders, including axion-like particles and light scalars from extended Higgs sectors.

10.3.4 Cosmology and astrophysics

Cosmology and astrophysics provide a wide range of opportunities to expand our knowledge of the fundamental laws of nature, both through direct searches for BSM physics and through tests of the SM in extreme conditions that are impossible to recreate in the laboratory. The impact of theoretical effort in cosmology and astrophysics over the past decade can be viewed through the lenses of (i) advancing our understanding of fundamental physics by forcing us to ponder extreme scenarios where, e.g., quantum effects and gravity must be considered simultaneously, (ii) developing new microscopic models that can potentially explain the outstanding problems facing our understanding of nature, and (iii) inventing new approaches to test our best-motivated theories, in addition to developing the theoretical tools needed to properly interpret the resulting data.

10.3.4.1 Dark matter

We have overwhelming evidence for the existence of cold and at most weakly interacting DM across a variety of astrophysical scales comprising $\sim 27\%$ of the energy density of the universe. The DM mass is constrained on the lower end to be larger than $\sim 10^{-20}$ eV and on the upper end to be smaller than $\sim 10^4 M_\odot$. We find ourselves at a unique point in history, where the existence of DM on astrophysical and cosmological scales is known and well characterized, but the microscopic nature of the DM is largely unconstrained, up to rough constraints on the DM mass and interaction strengths with itself and with ordinary matter. Over the past decades theorists have developed particle-physics-based models to explain DM that typically lead to faint but observable signatures. The types of signatures vary drastically depending on the DM model at hand, leading to a world-wide scientific program searching for evidence of particle DM across

laboratory experiments ranging from the LHC, to underground direct detection experiments, to precision laboratory experiments, to intensity frontier experiments. In many DM models there are direct or indirect astrophysical signatures, such as modifications to DM halo structure itself; electromagnetic, cosmic ray, and neutrino signatures in the case of annihilating, decaying, and converting DM; and even gravitational wave signatures associated with phase transitions in the early universe. DM may also be associated with new light physics, such as light mediators or ultralight particles, that may have effects ranging from modifying stellar evolution, to producing signatures in dedicated fixed target experiments, to adding extra radiation measured in the cosmic microwave background (CMB). Theoretical efforts to produce viable DM candidates have been the driving force behind numerous experimental and observational programs. Beyond the construction of specific DM models, theorists have played an especially important role in the past decade in proposing and helping implement specific experiments and astrophysical search strategies for covering some of the best motivated DM parameter space.

Weakly interacting massive particles (WIMPs) with electroweak scale masses and couplings that acquire their relic abundance through thermal freeze-out in the early universe have been considered the canonical DM candidates for decades, partly because solutions to the hierarchy problem (such as low-scale SUSY) naturally produce WIMP-like DM candidates. However, at present the search for WIMP DM is at a turning point, since both direct and indirect searches for SUSY and other TeV-scale models of naturalness have so far yielded no direct evidence, tightly constraining large areas of the parameter space of these models as well as the properties of a putative WIMP DM candidate. On the other hand, WIMP DM is very much not dead. Nearly-pure Higgsino DM serves as an illustrative example of a surviving WIMP DM candidate that serves as an exceptionally well-motivated target for upcoming experiments. Composite Higgs and Twin Higgs models also contain a variety of well-motivated DM candidates. One area with substantial theoretical effort and progress over the past decade has been the study of indirect detection of WIMP-like DM via annihilation or decay into high energy photons in the X-ray or γ-ray band. Theorists have been key parts of this effort, and have developed new analytical strategies and analysis tools for these searches. Progress in experimental tests of these two landmark signatures has been accompanied by a substantial broadening of astrophysical searches for the imprint of DM in cosmic rays.

The past decade has also seen enormous progress, led by theoretical efforts, in constructing models of particle dark matter that go beyond the WIMP paradigm. A notable variation is where the DM particle itself does not interact significantly with the SM, but instead it interacts with a secondary state, which itself has a standard freeze-out mechanism. If the mass of the secondary state is much heavier we get a secluded model with strongly suppressed direct detection rates. If instead the secondary state's mass is close to the DM mass we obtain a co-annihilation model. One popular class of models is based on the realization that $3 \to 2$ or $4 \to 2$ interactions (a phase of "cannibalism") can substantially influence the resulting DM relic density. Resulting models include SIMPs, co-SIMPs and ELDER. Another mechanism for generating DM is freeze-in. Here the dark sector is populated by the leakage of energy from the visible sector through sub-Hubble annihilations or decays of SM particles over time. These models (often also called FIMPs) include sterile neutrinos, singlet scalars, and various superpartners. Alternately, the observed dark matter relic abundance may be generated from a residual asymmetry. For example, the concept of asymmetric dark matter posits a common origin for the baryon content of the Universe and DM. An interesting mechanism for enhancing the late-time annihilation signal is the Sommerfeld enhancement, which happens when long range forces arise in the non-relativistic limit. Another important dynamical concept is Inelastic DM, when the scattering of DM on nuclei can only happen via an inelastic channel requiring a minimal threshold energy for the incoming DM particles, potentially suppressing certain direct detection cross sections. It is also possible that the DM is a stable bound state of a confining sector, where some symmetry guarantees the stability of this particle. They could either be dark pions, or more naturally dark baryons, or even dark glueballs. Another interesting possibility is atomic DM, formed by atom-like bound states of some hidden/mirror sector, most commonly two fermions oppositely charged under a $U(1)_D$ dark gauge symmetry.

10.3 Phenomenology

Perhaps the most striking progress in dark matter theory over the past decade has come from renewed attention to axionic, light, and ultralight DM. The QCD axion was originally introduced to address the strong-CP problem, but axion-like particles which do not couple to QCD are also motivated for purely theoretical reasons because they arise generically in the context of string theory constructions. They can also be very successful DM candidates, with their dynamics depending on the relation between the Peccei-Quinn (PQ) symmetry breaking scale and the scale of inflation. For a high PQ breaking scale one needs dedicated lattice-QCD calculations to determine the axion DM abundance, while for a low PQ breaking scale one needs dedicated simulations of the production of axion strings and domain walls. Such simulations have seen a revolution in their complexity and accuracy in the last decade, aided in large part by advances in high-performance computing, and these computations will improve further in the near future by leveraging computational and technological advances. Axion-like particles as well as a broader class of scalar and vector particles may also make up a sizeable fraction of the DM. Over the past decade "fuzzy DM" — ultralight dark matter with wavelength on astrophysically relevant scales— has received a wave of interest in part to explain a number of apparent failings of the standard cosmological model on small astrophysical scales. On the other hand, fuzzy DM has become increasingly constrained in the latter half of the past decade, thanks to theoretical efforts in understanding the astrophysical implications of fuzzy DM, cosmological and galactic-scale simulations incorporating fuzzy DM, and new data. It has long been understood that axions could leave detectable astrophysical signatures by modifying stellar cooling. The recent refinement of stellar and compact object cooling probes and the development of a number of novel astrophysical tests have combined to provide some of the strongest constraints on the QCD axion and ultralight scalars, vectors, and axion-like particles, apart from a narrow mass range probed by the ADMX experiment.

Traditionally, direct searches for axions fell into one of the following three classes: (i) light shining through wall experiments, (ii) axion helioscopes, and (iii) axion resonant microwave cavity haloscopes. Thanks to pioneering theoretical effort, followed by bold and innovative small-scale experimental programs, there now exists proposals for probing nearly the entire currently-allowable QCD axion mass range. An important theoretical observation at the beginning of the last decade was that the axion, while it solves the strong-CP problem by removing the time-averaged neutron EDM, leaves a time-varying, residual EDM when the axion is DM. This led to the proposal for the CASPEr experiment, which aims to detect the oscillating axion-induced EDM using a nuclear magnetic resonance based experiment. A similarly ground-breaking discovery came from the observation that by thinking more broadly about the modifications to Maxwell's equations in the presence of axion DM, experimental setups could in principle be constructed that would be sensitive to GUT scale axion DM using the axion-photon coupling. This became the basis of the ABRACADABRA 10-cm collaboration, whose initial demonstrator has already set world-leading limits on the axion-photon coupling. Other novel proposals in ultralight dark matter surround the idea that scalar dark matter coupled to the Standard Model can result in small periodic oscillations of fundamental constants such as the electron mass and the fine structure constant. Searches performed to date have taken advantage of precision measurement techniques such as atomic clocks to search new parameter space.

The indirect detection of DM annihilation or decay in the local universe through its imprint on cosmic rays is a key element of the program to detect and identify DM. In recent years, indirect detection analyses have made major progress in exploring the parameter space where signals are predicted in the most straightforward models, such as WIMP DM and sterile neutrino DM. Theorists have been key parts of this effort, and have developed new analytical strategies and analysis tools for these searches. Progress in experimental tests of these two landmark signatures has been accompanied by a substantial broadening of astrophysical searches for the imprint of DM in cosmic rays. Recent developments in DM model-building have expanded the range of DM annihilation and decay signatures that are of interest to indirect detection, providing models with novel spectral signatures, signatures that populate new kinematic areas, signatures in novel final states, and signatures with unusual spatial distributions. It has long been understood that axions could leave detectable astrophysical signatures by modifying stellar cooling. However, in the past decade a

number of novel astrophysical probes of axions and axion DM have been developed, in part because of input from string theory motivating axion-like particles and broader parameter space for the QCD axion. At the same time, the stellar cooling probes have been refined, such that at-present the strongest constraints on the QCD axion and axion-like particles, apart from a narrow mass range probed by the ADMX experiment, arise from astrophysical probes. Theorists have been crucial in developing the ideas behind these searches and implementing them with astrophysical data.

Another key area where a new approach to DM model building and detection has seen rapid progress is that of sub-GeV dark sectors, which contain new singlets under the SM gauge symmetry that may or may not have self interactions. If DM resides in the dark sector it can talk to the SM through a number of weakly-coupled portals. Dark sector constructions often contain light mediators, such as dark photons, that can themselves be directly probed by experiments. Theorists have not only developed models of sub-GeV dark sectors, but also played important roles in devising new approaches to search for them, from new types of direct detection to accelerator production of dark matter and accelerator searches for the mediators themselves.

Prior to the early 2010's, the experimental effort for seeking the direct detection of DM was singularly focused on elastic or inelastic scattering off of nuclei. However, at the beginning of the past decade, motivated by sub-GeV dark sector modeling efforts, a range of theoretical proposals was put forth for detecting novel inelastic DM interactions with electrons in materials. The advantage of scattering off of electrons for light DM is clear: since the electron has less mass, it acquires a larger recoil energy relative to nuclei during scattering processes. Since electrons tend to be bound, DM-electron processes tend to be inelastic. It was also proposed that semi-conductor targets might be even better suited for light-DM searches, since the DM would in principle just need enough energy to push an electron over the band-gap in order to produce a detectable signature, though calculating the scattering rates is non-trivial and connects with cutting-edge topics in condensed matter physics. The theoretical work showing the promise of semiconductor targets for light DM motivated an experimental research program to try to detect one or few electron events. The detection of single electron scattering events is now possible, as demonstrated by the SuperCDMS and SENSEI collaborations.

A second path to detecting sub-GeV dark matter is through its production at accelerators. Unlike direct detection, where light-DM signals are kinematically challenging to detect, the energy required to produce light DM at accelerators is achievable at many facilities, including both flavor factories and fixed target experiments. Instead, the challenges of accelerator-based detection stem from the very weak couplings typically expected for light DM. Theoretical studies were the first to note that, despite these small couplings, accelerator-based neutrino experiments had sufficiently high luminosity to produce a secondary beam of DM particles, leading to a potentially observable scattering rate in downstream detectors. This realization motivated the MiniBooNE-DM experiment, as well as searches for DM at the COHERENT and CCM detectors. A second approach to searching for light DM at accelerators, the missing energy/momentum strategies, leverages the distinctive kinematics of DM production reactions to identify them with high efficiency in a lower luminosity lepton beam. Theorists again played important roles in developing these strategies, exemplified by NA64 and LDMX, and understanding their ultimate capabilities.

The realization that DM may reside in a dark sector weakly coupled to the SM has also led to new pathways to discovery for the mediator itself at accelerator-based experiments. The idea of looking for weakly-coupled mediators is distinct from the traditional approach to new-physics searches at colliders, which tend to focus on the energy frontier and probing new, relatively strongly coupled, but massive states. This led to a number of theoretical proposals for dedicated or parasitic dark-sector collider-based searches over the past decade, many of which have already turned into actual experiments or are funded and in construction phases, for example HPS, FASER, APEX or DarkQuest.

10.3.4.2 Quantum sensing

As discussed in the preceding subsection, there is a plethora of examples where theorists have instigated new DM experiments. The development of quantum sensing technologies, in particular, has opened the door to new opportunities to search for new particles or interactions that arise in well-motivated BSM theories, enabling novel experiments, detectors, and measurements. Here high energy theorists are playing a central role in proposing and guiding such experiments in the pursuit of searches for new light matter particles (axions, axion-like particles, dark photons, milli-charged particles), dark matter, gravitational waves over a large range of frequencies, and tests of quantum mechanics and of gravity – the list is long. The envisioned experiments employ diverse quantum sensing platforms and technologies, including atom interferometers, atomic clocks, novel condensed matter systems, SRF cavities, dielectric stacks, dish antennas, quantum optics, quantum spin gyroscopes, and single particle traps among others. They typically include interdisciplinary efforts connecting theorists and experimentalists from HEP, AMO, and condensed matter. As proposals are being turned into experiments, theorists continue to provide guidance and interpretation, strengthening the connections between theory and experiment to the benefit of both.

10.3.4.3 Cosmology

Cosmological observations offer the unique opportunity to reconstruct the history of the universe and the laws that shaped it. It is through our theoretical understanding of the forces that shaped the cosmos that we can then reconstruct the expansion history, search for new particles and forces, identify new objects, and more.

The cosmic microwave background has been the main driving force in cosmology to date. The impact of new CMB data will depend increasingly on theoretical techniques to isolate different physical effects that alter the observed high-precision CMB maps. CMB photons are both gravitationally lensed and scattered by the matter between us and the surface of last scattering. Ongoing theoretical work has shown how these effects can be removed from the CMB maps using their statistical properties and frequency dependence, in the process creating new maps for the distribution of matter in the universe. Galactic foregrounds, particularly from dust, present an additional challenge to CMB measurements. Our understanding of these dust signals from first principles is limited but has been bolstered by simulations and data-driven techniques.

Gravitational waves produced after inflation are an increasingly compelling window into the history of the universe. This includes both gravitational waves produced during reheating and/or phase transitions in the early universe and from mergers of black holes, neutron stars, and/or more exotic objects. Given that the universe is transparent to gravitational waves, this presents a unique opportunity to probe important events throughout cosmic history and not just after recombination. Generating templates at the accuracy needed for future observatories will require a variety of theoretical tools that connect observational needs to the most fundamental questions about the nature of gravity. The current state of the art has been pushed forward by a combination of EFT and amplitudes techniques. The calculation of the waveform from amplitudes techniques also benefits and exposes properties of the double copy.

Large scale structure surveys that provide the distribution of galaxies at lower redshifts are increasingly important windows into the universe. In many ways, the raw statistical power of large scale structure surveys rivals the CMB today and will rapidly exceed it with upcoming surveys. Unfortunately, our ability to use these maps to understand the universe is limited by our understanding of nonlinear structure formation and astrophysical uncertainties, not simply statistics. Theoretical insights paired with increasing sophisticated simulations have made many new and more powerful analyses possible, but much work remains if we are to harness the full power of these surveys for fundamental physics. On the largest scales, effective field

theory and perturbation theory techniques are sufficient to model both the DM, baryons and tracers thereof. Work on the effective theory of large scale structure has made the regime of validity transparent, along with the systematic expansion in the density, and has opened the door to analyses of the full-shape matter power spectrum and bispectrum that have never previously been done. In addition to modeling the LSS perturbatively, theoretical understanding of both the signal and the non-linear evolution have yielded a number of protected observables, quantities that we can measure that are largely not impacted by nonlinear evolution, of which the baryon acoustic oscillations are one of the most significant examples.

On small scales, the density contrast becomes order one and perturbative methods break down. In addition, on these nonlinear scales baryonic feedback significantly alters both the distribution of DM and the formation of galaxies. DM-only simulations have been important in understanding this regime, but have left a number of outstanding problems concerning the distribution of matter on small scales, including the DM at cores of galaxies and the number of satellites. Simulations of DM and baryons, including feedback from active galactic nuclei and supernovae, have suggested that baryons could play a significant role in addressing these problems. In contrast, a number of models of DM have been proposed that would alleviate these tensions between simulations and observations, by introducing small- scale cutoffs in the matter power spectrum, giving DM self-interactions, or both. Continued development of simulations on both cosmological and galactic scales are therefore essential to our understanding of the fundamental physics of DM and the astrophysics of galaxies and galaxy clusters.

10.3.4.4 Inflation and acceleration - relation to fundamental theory

The expansion of the universe is accelerating today and was very likely accelerating in the past, due to dark energy and inflation respectively. These epochs present unique challenges for fundamental physics, both qualitatively and quantitatively. Recent progress has been driven by a variety of advances connecting cosmology to the many corners of the theory frontier. Yet, understanding quantum gravity in cosmological spacetimes remains one of the largest and most important unsolved problems in high energy physics, as it unites both basic theoretical questions, cosmological observations, and even the origin and fate of the universe.

In recent years, our understanding of inflation has been significantly enhanced by the insights of effective field theory, and the EFT of Inflation has been developed. Inflationary model building makes extreme demands of the effective field theories that describe the inflationary mechanism, which has inspired a wide range of work investigating the space of consistent EFTs and their origins from a UV complete theory like string theory. The search for explicit models has yielded a variety of novel ideas that can be studied and generalized in the context of inflationary EFTs, and yield new signals and analyses of cosmological data. In recent years, the constraints of self-consistency and the existence of a UV completion have been applied directly to the EFT of inflation and the cosmological correlators. Often characterized as the cosmological bootstrap, this approach shares common elements with the amplitudes and conformal bootstrap programs. One promising opportunity at the intersection of fundamental physics and cosmological observations is the impact of the particle spectrum during inflation, including light and heavy fields, on non-Gaussian cosmological correlators.

The discovery of the accelerated expansion of the universe today further challenges our under- standing of fundamental physics. The small size of the cosmological constant has resisted a natural explanation. In addition, evidence from string constructions and other theoretical challenges have suggested that perhaps de Sitter space is fundamentally unstable and/or is one of many accelerating regions. It remains entirely possible that our current acceleration is more analogous to a second inflationary period and that de Sitter-like regions do not occur at all. Observational constraints on this possibility are encoded in a similar

effective field theory description that is constrained by a variety of observational and gravitational probes. The challenges associated with de Sitter range from perturbation theory on a fixed de Sitter background all the way to non-perturbative effects in a quantum theory of gravity. In recent years, significant progress has been made understanding the structure of perturbation theory in a fixed de Sitter background. Using EFT or diagrammatic techniques, one can see both the IR and secular terms that arise in the cosmological slicing of dS can be resummed using the framework of Stochastic Inflation.

10.3.5 Neutrino physics

The discovery of nonzero neutrino masses requires new fundamental fields and new interactions. We know very little about this new physics other than the fact that it exists. Among the goals of neutrino theory is to identify the different hypothetical degrees of freedom and interactions responsible for nonzero neutrino masses. More progress requires a coherent theoretical and phenomenological effort to establish connections to other outstanding questions in fundamental particle physics. On the phenomenology side, massive neutrinos must have nonzero dipole moments, and, since neutrinos and charged leptons are connected, neutrino mixing naturally leads to charged-lepton flavor violating processes. Being associated with neutrino masses, these quantities will likely receive contributions from the underlying new physics. Interpreting results from the corresponding experimental efforts in terms of the possible BSM theories requires robust theoretical predictions of the SM contributions to these processes. The coming precision era of neutrino oscillation experiments promises precise measurements of fundamental neutrino mass and mixing parameters, providing important information on the nature of these particles. In order to fully exploit the experimental measurements, precise theoretical predictions of the underlying neutrino-nucleus cross sections (including their energy dependence) are needed, which poses a significant theoretical challenge, as described below.

10.3.5.1 Neutrino masses and flavor models

Within an effective theory approach (where the absence of any new light degrees of freedom beyond the SM is assumed) the neutrino masses originate from the unique dimension five operator of the form $-(LH)^2/(2\Lambda)$ with a suppression scale $\Lambda \sim 10^{15}$ GeV. In order to generate this operator one can safely conclude that there must be new degrees of freedom with masses at or below 10^{15} GeV. These could be either a neutral or a triplet fermion, or a triplet scalar, giving rise to various types of see-saw mechanisms. However, the mass of these new degrees of freedom could be anywhere in between the eV and the 10^{15} GeV scale. Different new-physics scenarios leave imprints in different types of particle and nuclear physics probes and may be related to other outstanding questions in fundamental particle physics. A distinct possibility is that the neutrino mass is not captured by the effective operator, but instead there are new light degrees of freedom (right handed neutrinos) which form Dirac neutrinos together with the SM neutrinos, in which case a $\mathrm{U}(1)_{B-L}$ symmetry is preserved. The Dirac neutrino scenario leads to the theoretical puzzles of why the relevant Yukawa coupling is many orders of magnitude smaller than even the electron Yukawa coupling, and how the exact global $\mathrm{U}(1)_{B-L}$ symmetry remains unbroken by quantum gravity.

The flavor symmetry breaking pattern of the lepton sector is quite different than for the quarks, and are often a more natural fit for discrete flavor symmetries, which circumvent some of the challenges faced by continuous symmetries. This approach to flavor also has its limitations including a certain level of arbitrariness when it comes to choosing how the symmetries are broken. Flavor symmetries also provide concrete precision-targets for next-generation neutrino oscillation experiments. One example is the currently unknown CP-odd phase δ that parameterizes CP-violating effects in neutrino oscillations, and different

flavor models make qualitatively different predictions for δ. Consequences of flavor symmetries may also translate into relations among the different masses and mixing which might be tested experimentally.

10.3.5.2 Neutrino phenomenology

Neutrino oscillation experiments provide all affirmative information we have on neutrino masses. More, better neutrino oscillation data are expected in this and the next decade. Theory played a central role in the development of the formalism of neutrino oscillations, including the solution to the twentieth-century solar and atmospheric neutrino puzzles. This role is expected to persist and evolve as the oscillation probes grow more sophisticated and diverse. Different neutrino-phenomenology research groups provide the best-fit values for the different oscillation parameters that are used by the particle physics community as a whole. New neutrino oscillation data can also reveal more new physics in the neutrino sector, including new weaker-than-weak neutrino–matter interactions that modify neutrino production, detection, and flavor-evolution, new light neutral fermions that lead to the presence of new oscillation frequencies or to the apparent non-unitarity of the leptonic mixing matrix, or allowing for the possibility that neutrinos have a finite lifetime.

Neutrino theory also aims at interpreting unexpected results in neutrino experiments collectively referred to as the short-baseline anomalies. While there is currently no outstanding solution to the short-baseline anomalies, it is possible that the correct answer is still to be uncovered, that may include the existence of new physics. These could include, for example, new neutrino states that participate in new interactions. Since neutrinos interact only via the weak interactions, neutrino scattering experiments are especially sensitive to new, weaker-than-weak interactions mediated by hypothetical light or heavy new particles. Neutrino scattering experiments (which are fixed-target spanning an energy range of more than 20 orders of magnitude) can reveal the existence of new interactions, new neutrino properties, or new particles.

As explained, neutrino masses imply the existence of new particles. If these are light enough and strongly-coupled enough, they can be produced and detected at high energy colliders. For example right-handed neutrinos with Majorana masses of order tens to thousands of GeV could be produced at the LHC and other high energy colliders, just like ordinary neutrinos. Neutrinos and charged-leptons are intimately connected. The fact that neutrinos mix, for example, implies that lepton-flavor numbers are not conserved in nature so flavor-violating processes involving charged-leptons are also guaranteed to occur. In the absence of new interactions, however, the expected rates for charged-lepton flavor violating (CLFV) process, including $\mu \to e\gamma$, $\mu \to 3e$, and $\mu \to e$ conversion in nuclei, are tiny. New physics, including the interactions and degrees of freedom that may be responsible for nonzero neutrino masses, can lead to much larger rates for CLFV, often providing the best constraints on some models. Neutrino oscillation experiments often also allow other particle physics measurements and searches for new phenomena, many of which are only peripherally related to neutrinos. For example, near detectors in neutrino oscillation experiments are an excellent place to search for light, hidden sector particles, including a dark photon produced in neutral pion decay, while far detectors are ideal for monitoring a large number of nucleons in search for proton decay and other baryon-number violating processes.

10.3.5.3 Neutrinos in astrophysics and cosmology

The past decade has seen important advances in neutrino astrophysics and cosmology. These advances inform us about the nature of the sources from which the neutrinos originate, but also inform us on the properties of neutrinos. High energy neutrinos (from GeV and above) range from atmospheric to GZK neutrinos, and are usually correlated with cosmic rays. IceCube provides very high statistics atmospheric

data at energies from a few GeV to a few TeV, which can be used to reduce some of the systematic uncertainties associated with atmospheric neutrinos, also opening up the possibility of measuring a larger subset of oscillation channels, including $\nu_\mu \to \nu_\tau$. Over the last decade IceCube also observed neutrinos with energies well above a TeV coming from outside our galaxy, which provide a unique avenue to probe BSM effects, given the very long distances traveled by the neutrinos, as well as their ultra-high energies.

The detection of low-energy astrophysical neutrinos is an experimental and theoretical challenge onto itself; theory and phenomenology is required in order to understand how these neutrinos "look" inside different detectors. Supernova neutrinos provide a unique laboratory for neutrino physics and astrophysics, since apart from the Big Bang supernovae are the only environment in the universe where neutrinos are in or near thermal equilibrium conditions. The detection of neutrinos from the next individual supernova contains invaluable information on neutrino properties. However extracting information will require understanding the evolution of neutrino flavor inside the supernova explosion. Solar neutrinos already found spectacular application by pinpointing the LMA-MSW solution to neutrino flavor transformation from the Sun to the Earth, nevertheless still there are outstanding questions that surround some of the data.

Cosmological neutrinos produced in a thermal spectrum shortly after the Big Bang contain a wealth of information on particle physics, astrophysics and cosmology. Neutrinos contribute a significant component of the energy density in the early universe, which can be observed through precision measurements of the CMB and through other probes of the recombination of the universe. Neutrinos also affect the growth of structure through a change in the background expansion rate of the universe, and through their significant thermal velocities. Upcoming cosmic surveys such as CMB-S4, Euclid and the Vera Rubin Observatory will be sensitive to the sum of the neutrino masses. Extracting neutrino masses from these cosmic surveys is a nontrivial exercise that requires dedicated theoretical analyses and computations, involving for example, many-body physics and nonlinear dynamics.

With their vastly disparate energy scales, observations of astrophysical and cosmological neutrinos provide a wealth of information that is complementary to terrestrial experiments, entwining astrophysics, cosmology, and particle physics phenomenology. Theory and phenomenology play a key role in using this information to deepen our understanding of neutrino properties and interactions. In addition, theoretical work at this interface may yield insights into the properties of astrophysical objects and explosive phenomena and of the medium the neutrinos traverse.

10.3.5.4 Neutrino cross sections

Maximizing the discovery potential of neutrino experiments in the coming precision era requires theoretical predictions for the underlying neutrino-nucleus cross sections with commensurate (or better) precision to experiment. The large range of neutrino energies makes this a complicated task, requiring a coordinated effort from phenomenologists, lattice field theorists, nuclear theorists, and computational theorists working on event generators. To understand the energy dependence of the cross sections, separate theory inputs for the processes which dominate at the different energy scales are needed. The range covers coherent and inelastic scattering at $\lesssim 100$ MeV, quasi-elastic scattering (QE) dominated by single-nucleon knockout processes at $0.1 - 1$ GeV, two-nucleon emission and resonant production at $1 - 3$ GeV, shallow inelastic scattering (pion production) at $\gtrsim 3 - 5$ GeV, and deep inelastic scattering (DIS), where the neutrino can resolve the individual quark constituents of the nucleon at $\gtrsim 5$ GeV. Each of these regimes requires knowledge of both the nuclear ground state and the electroweak coupling and propagation of the struck nucleons, hadrons, or partons through the nucleon. The range of challenges is extreme; QE scattering and DIS are conceptually the easiest to understand, but also require nonperturbative inputs to quantify. In order to obtain precise theoretical cross section predictions with fully quantified uncertainties, a robust

pipeline is required combining inputs from perturbative and nonperturbative QCD and nuclear EFT with event generators. Ultimately, precise predictions of inclusive and exclusive cross sections across a wide range of kinematics are required for the success of the precision era of neutrino experiments.

Bridging the gap from precise theoretical predictions to experimental data requires the development of sophisticated event generator tools. The current- and next-generation neutrino experiments are reaching a point in which statistics are no longer the dominant uncertainty. The largest systematic uncertainty is the modeling of the primary interactions and the propagation of hadrons from the primary interaction out of the nucleus. Improving this falls under the purview of event generators. Further development of neutrino event generators is essential to meet the needs of DUNE and the SBND program. Additionally, with the general purpose near detector of DUNE, it will be vital to develop the ability to efficiently investigate BSM processes through automation developments within generators, similar to how this is handled at the LHC. Finally, there are many open questions that can be best answered by theorists involved in event generation, such as the modeling of hadronization at $Q^2 < 10$ GeV^2 and the matching from shallow inelastic scattering to DIS.

The theoretical description of the large nuclei employed as targets in neutrino scattering experiments is based on nuclear many-body effective theory and requires nonperturbative inputs for single- and few-nucleon form factors and matrix elements. While electron scattering experiments provide precise inputs for vector current elastic form factors, axial current elastic form factors are not well known. Dedicated efforts already exist to calculate the needed form factors in lattice QCD with good control over systematic errors. Lattice-QCD based nucleon form factors and quasi-elastic scattering inputs for nuclear many-body theory with total uncertainties at the few-percent level are within reach of current theoretical methods and available computing resources (see Sec. 10.4.1).

Resonant and non-resonant nucleon axial transition form factors, needed at higher neutrino energies, are also accessible from lattice QCD. While first results are already available, more effort is required to deliver results with complete error budgets. Nuclear many-body theory predictions on nuclear modifications to resonant and non-resonant pion production and absorption processes are also needed. Lattice-QCD studies of PDFs, relevant at yet higher neutrino energies in the DIS region, are rapidly maturing. The transition regions between low- and high-energy theories use different degrees of freedom to describe neutrino-nucleus interactions which poses an important theoretical challenge requiring further studies.

10.3.5.5 Neutrinoless double beta decay

The next generation of tonne-scale neutrinoless double-beta ($0\nu\beta\beta$) decay experiments has the opportunity to answer fundamental questions about the nature of neutrino masses: observation of $0\nu\beta\beta$ decay will imply that neutrinos are Majorana particle. In addition these experiments are sensitive to a variety of lepton-number-violating (LNV) mechanisms, including the standard scenario driven by the exchange of light Majorana neutrinos, low-scale seesaw scenarios with light sterile neutrinos below the electroweak scale, and models of physics beyond the Standard Model (BSM) with new degrees of freedom at the TeV scale. The interpretation of $0\nu\beta\beta$ experiments demand an ambitious theoretical program including further developing particle-physics models of LNV, and computing $0\nu\beta\beta$ rates with minimal model dependence and quantifiable theoretical uncertainties.

10.4 Computational theory and Quantum Information

Computational theory, the third Theory Frontier theme, seeks to quantify predictions of the underlying QFT in regions beyond the reach of semi-analytic methods. As such it typically starts from a well-defined underlying theoretical structure which can be evaluated using computational methods.

All areas of high energy theory benefit from or contribute to the development of computational methods to some extent. In collider phenomenology and precision phenomenology based on multi-loop perturbation theory, computational methods are crucial in all components that are needed to obtain reliable theoretical predictions. A brief overview of the challenges surrounding event generators, which connect theoretical calculations to experimental observations, is given in Sec. 10.3.3. The multi-loop amplitudes at the core of the perturbative calculations contain complex mathematical structures and theoretical structures requiring specialized computational strategies. The integration over final state momenta to obtain the hard, parton-level cross sections is further complicated by the presence of infrared and collinear singularities. Finally, the PDFs are nonperturbative inputs, currently obtained from fits to large experimental data sets, presenting their own set of computational challenges. Cosmological, astrophysical, and DM simulations are central to theoretical research in astro-particle physics and cosmology. The development and refinement of computational methods for these simulations is crucial to progress in this area, as discussed in Sec. 10.3.4.

A classic computational theory example is Lattice Field Theory (LFT). The standard approach to LFT starts from the Euclidean (imaginary-time) path integral to study nonperturbative effects of strongly coupled theories of interest, including (but not limited to) QCD, in Monte Carlo simulations on classical computers. Quantum Computing and Quantum Simulation of QFTs hold great promise to overcome limitations of Euclidean LFT for the study of systems such as real-time scattering dynamics, finite density systems (quark gluon plasma, neutron stars), and QFTs with θ terms, among others.

New theoretical methods and insights are also important drivers of progress in computational theory, while computational demands can provide motivation for theoretical work. For example, insights gained from the amplitude program developed in fundamental theory have enabled progress towards $\mathrm{N^3LO}$ calculations in multi-loop collider phenomenology. On the other hand, the complex analytical structures of the multi-loop amplitudes and partonic cross sections invite development of novel EFTs and the study of special mathematical functions. More recently, amplitude methods are employed to obtain gravitational wave templates. To list just one example for lattice QCD, the connection between discrete finite volume spectra of multi-hadron systems to scattering phase shifts, discovered long ago by Lüscher, has been developed into a powerful formalism to obtain scattering amplitudes, resonance properties, and weak decay amplitudes into resonances, however limited at present to systems with at most three hadrons. A new theoretical method relates finite-volume matrix elements of current-current operators to inclusive scattering or decay rates, which could open up an entirely new set of observables to lattice-QCD studies in the coming decade. Connections between fundamental theory and computational theory are discussed in Sec. 10.2.1 for the numerical conformal bootstrap. While insights from fundamental theory can potentially drive new computational methods, computational theory, in turn, can provide powerful tests of analytic predictions of the properties or dynamics of QFTs (or other theoretical structures in question), potentially yielding a deeper understanding of the structure of the underlying QFT.

Computational theory is tied to enabling technologies, both driving and benefiting from ever more sophisticated and powerful platforms for classical computers, quantum computers and quantum simulators, as well as algorithm development and code optimization. In the development of LFT as a general purpose, precision tool over the past 40 years, interdisciplinary efforts connecting to computer science and applied mathematics were important drivers of progress. A famous example is the co-design of the IBM Blue Gene

series in the 2000s. Recent examples involving Machine Learning and Artifical Intelligence (ML/AI) are discussed below.

10.4.0.1 Machine Learning and Artificial Intelligence

Machine Learning and Artificial Intelligence describe a broad class of learning algorithms, including for example, deep learning architectures based on complex neural networks with many layers. ML methods have been developed for and used in high energy experimental data analyses for many years. ML is now playing an increasingly important role in all areas of high energy theory, in particular, those that rely on theoretical simulations or numerical analysis. In particular, novel ML methods are being developed or adapted in first-principles simulations in lattice field theory and event generation. In LFT, ML applications have been developed for all stages of the computations, including the generation of gauge fields and correlation functions as well as the numerical analysis needed to extract the physical observables of interest from the underlying correlation functions. Similarly, in standard event generators, all modules can be improved through ML, including phase space sampling, scattering amplitudes, loop integrals, parton showers, parton densities, and fragmentation. End-to-end ML generators, which use generative networks to directly generate parton-level events, complement standard generators in important ways. The generative ML models that have been developed for efficient sampling of gauge fields in LFT or phase space in event generators are based on new symmetry-preserving ML architectures that can include correction steps to guarantee exactness. This development is a nice example of cross-disciplinary synergy, as these new networks are finding applications in other fields of science and also in industry, inviting further cross-disciplinary collaboration.

Other examples, include jet structure in collider phenomenology, where, as discussed in Sec. 10.3.3, ML is used to construct new data-driven observables building on synergy between theory and experiment. For BSM phenomenology studies, generative ML and other simulation-based inference frameworks have also proven useful in efficiently sampling high-dimensional BSM parameter spaces (e.g. supersymmetric theories) to check for consistency with experimental data. In cosmology, ML networks can be used to accelerate hydrondynamics simulations, which can, in turn be used in simulation-based inference frameworks to constrain cosmology and galaxy formation parameters.

10.4.1 Lattice Field Theory (LFT)

The development of computational methods for the study of lattice field theory was originally motivated by the desire to understand QCD in the nonperturbative regime. Since then, lattice QCD has been developed into a precision tool with applications to a broad range of observables. However, LFT is also used to study other QFTs with interesting, strongly-coupled dynamics, as we describe in the next subsection.

10.4.1.1 Lattice QCD

Lattice QCD is strongly connected to Phenomenology (the second Theory Frontier theme), as nonperturbative effects from QCD are ubiquitious wherever quarks or hadrons are involved. Thanks to remarkable progress in the past decade, lattice QCD provides essential inputs for quantities in all areas of Phenomenology discussed in Sec. 10.3. In the coming decade, the list of quantities for which lattice-QCD inputs meet the precision goals of current and planned HEP experiments is expected to grow significantly, a result of theoretical, computational and technological advances as well as continuing dedicated efforts.

In particular, lattice QCD plays a crucial role in interpreting experimental measurements in flavor physics, where physical processes involve hadrons in the initial or final states, or where the effects of virtual hadrons are important. Following decades-long, sustained efforts in the US (and internationally), precise lattice-QCD results are now available for a large number of hadronic matrix elements relevant for weak decays of light, strange-, charm-, and beauty-flavored hadrons, in all cases with completely quantified error budgets and in some cases with commensurate (or better) precision compared to experiment, hence maximizing the discovery potential of the experimental program. With one notable exception in the kaon system discussed below, the majority of results concern "simple quantities", defined as observables involving local operators with at most one hadron in the initial and final states respectively, which are (almost) stable under the strong interactions. These lattice-QCD results can either be used in determinations of fundamental parameters of the SM (when combined with corresponding experimental measurements) or to confront SM theory with experiment. Indeed, subpercent calculations of light-meson decay constants and semileptonic form factors have enabled precise determinations of CKM elements from the corresponding experimental measurements. Subsequent unitarity tests for the first row of the CKM matrix have recently yielded a surprising tension, prompting further investigations. Lattice-QCD results also enable precise SM predictions for rare decay processes, and improve SM predictions for the LFU testing ratios discussed in Sec. 10.3.2. Here the comparison between SM theory and experiment provides stringent constraints on BSM theories or could yield discovery of new physics, should a significant ($> 5\sigma$) disagreement between theory and experiment be observed. Within the next five years, (sub-)percent-level lattice-QCD results will become available for the whole suite of semileptonic B, B_s, D, D_s form factors and mixing matrix elements, given continued, sustained effort. Similar calculations of baryon form factors, while less precise, are also feasible with current methods. These results will complement the expected experimental measurements at Belle II, LHCb and BESIII, enhancing the discovery potential of these experiments. They may also shed light on the observed tensions between determinations of the CKM parameters $|V_{cb}|$ and $|V_{ub}|$ from exclusive vs. inclusive semileptonic B-meson decays, respectively. Lattice-QCD calculations of inclusive B-meson decay rates could provide more direct probes of the exclusive-inclusive tensions. New theoretical methods for such computations are under active development and may provide a path towards such results.

The muon's anomalous magnetic moment (a_μ), with a tantalizing 4.2σ tension between SM theory and experiment, is a prominent example of the discovery potential of precision physics. The anomaly arises from contributions of virtual particles, where all SM particles participate. The uncertainty in the SM prediction is driven by low-energy hadronic contributions, which are difficult to quantify precisely due their nonperturbative nature. Historically, in lieu of direct calculations, dispersion theory combined with data measurements of $\sigma(e^+e^- \to \text{hadrons})$ (so-called data-driven evaluations) were used to quantify the dominant hadronic vacuum polarization (HVP) contribution to a_μ. Indeed, the significance mentioned above is obtained from dispersive evaluations of HVP based on current, precise cross section measurements. While most existing lattice-QCD results for HVP are too uncertain for a meaningful comparison, a first lattice-QCD calculation with sub-percent precision is now available, albeit in tension with the data-driven prediction implying a reduced significance with the experimental average. This surprising result is currently being scrutinized in independent lattice-QCD calculations with commensurate (or better) precision. Indeed, given the dedicated efforts by the lattice community, it is expected that lattice-QCD results for HVP will meet the target precision set by the Fermilab experiment, provided that the different lattice-QCD results agree with each other. Here the comparison between lattice-QCD and data-driven HVP results will be crucial to the interpretation of the experimental measurement of a_μ.

A growing number of lattice-QCD calculations of increasingly complex quantities with control over systematic errors are becoming available. Prominent examples are results for the $\Delta I = 1/2$ rule in nonleptonic kaon decay and the direct CP-violation parameter ϵ'/ϵ in the kaon system. They were made possible, in part, by theoretical developments, including relating finite volume matrix elements to decay amplitudes and the formulation of chiral fermions. There are many other quantities for which sufficiently precise lattice-QCD

calculations are needed to interpret quark- and lepton-flavor physics experiments. These needs are being addressed in a broad program of lattice-QCD calculations, which includes development work to establish the needed precision or expand methodologies to increase the scope of the calculations. Ongoing work includes projects to compute semileptonic form factors for decays of heavy-flavored hadrons into vector-meson final states, isospin-breaking corrections (including radiative QED effects) in simple weak decay matrix elements, and rare kaon decay amplitudes, among others.

Precision tests of the SM nature of the Higgs boson confront measurements of Higgs-boson branching fractions with SM expectations, which are affected by parametric uncertainties from the quark masses and α_s. Lattice-QCD based determinations of these fundamental parameters already meet the precision demands of the LHC program in the coming decade. Theoretical predictions of, for example, LHC cross sections or neutrino-nucleus cross sections in the deep inelastic regime require x-dependent PDFs as inputs. These nonperturbative functions are related to light-cone correlations of quark and gluon fields inside a given hadron, which are difficult to compute directly in a Euclidean framework, such as lattice QCD. The past decade has seen the development of several promising approaches and intense efforts to implement them in numerical computations and study their relative merits. They include quasi-PDFs which are related to the usual PDFs via a new EFT, "Large Momentum EFT"; pseudo-PDFs, related to Ioffe-time distributions; and Compton amplitude and current-current matrix elements coupled with OPE and/or inverse transforms, for which new strategies are under active development as well. In addition, other multi-variable matrix elements, such as GPDs (Generalized Parton Distributions) and TMDs (Transverse Momentum Distributions) are also being studied. There are various technical, computational, and theoretical challenges associated with each approach, and ongoing efforts seek to obtain lattice-QCD results with control over the dominant systematic effects. Once such results are available, they can be tested against PDFs obtained from experimental data. Lattice-QCD results for PDFs will be particularly important in regions that are less-well determined from experimental data.

Nucleons and nuclei are commonly used in searches for violations of fundamental symmetries of the SM and for BSM signatures. Thanks to growing, dedicated efforts, lattice-QCD results with few-percent-level uncertainties have recently become available for a key nucleon quantity (the iso-vector axial charge, g_A). This can be regarded as marking the start of the precision era for lattice-QCD calculations in the nucleon sector. Assuming continued effort, coupled with increases in computational resources, and leveraging new computational methods to address the signal-to-noise problem in nucleon and nuclear correlation functions, we expect that the coming decade will see a growing number of lattice-QCD results for nucleon matrix matrix elements with completely quantified uncertainties, possibly reaching, in some cases, percent-level uncertainties. Among these quantities are the nucleon vector, axial-vector, and pseudoscalar form factors, which are needed as inputs for theoretical predictions of neutrino-nucleus cross sections as already discussed in Sec. 10.3.5; nucleon EDM matrix elements of SM and BSM operators, relevant for planned neutron and proton EDM experiments; the scalar, axial, vector, tensor charges of the nucleon, which are important to interpret high-precision neutron-decay experiments yielding constraints on CP violation and BSM interactions; and spectroscopic studies of excited state hadrons and resonances relevant for precision EW hadronic decay processes and for neutrino-nucleus cross sections. Nucleon matrix elements describing proton decay, neutron-antineutron oscillations, muon to electron conversion, and neutrinoless double beta decay are examples of other quantities where lattice-QCD inputs are critically needed for theoretical prediction of the corresponding rates. Based on ongoing efforts, it is entirely reasonable to expect that lattice-QCD results with fully quantified uncertainties will become available in the coming decade for at least some of these other quantities.

Given the examples above, it is clear that theoretical calculations of a wide range of nucleon and nuclear properties, which are also of interest in the context of nuclear physics, are essential inputs for important, low-energy particle-physics experiments. These experiments often use heavy nuclear isotopes, e.g., Argon at

DUNE and Germanium in certain neutrinoless double-beta decay and dark-matter detection experiments. In order to obtain quantitative information about the underlying short-distance (B)SM physics, the nuclear responses to the EW probes must be quantified with sufficient precision. An *ab-initio* QCD description of these complex nuclear systems is well out-of-reach of current lattice-QCD methods. More suitable theoretical treatments account for the vast range of scales involved, and use nuclear many-body theory and nuclear effective theory to capture the very low-energy nuclear effects. The role of lattice QCD then is to provide the non-perturbative inputs for matrix elements of the various SM and BSM operators in single- and few-nucleon systems to constrain the corresponding EFTs. These EFTs can then be used in many-body nuclear-structure calculations to evaluate the relevant observables in heavier isotopes. This program requires a coordinated effort between the high-energy and nuclear theory communities. First lattice-QCD results for matrix elements of two-nucleon systems as well as of light nuclei ($A \leq 4$) already exist, albeit with unphysically heavy pion masses and other limitations. Further efforts to develop more efficient computational strategies as well as significantly larger computational resources are required in order to obtain lattice-QCD results for such systems with full control over the statistical and systematic uncertainties.

10.4.1.2 Lattice Field Theory beyond QCD

LFT provides access to the nonperturbative properties of asymptotically free Yang-Mills theories, where the gauge group (typically SU(N_c), but not limited to it), the number of fermions (N_f) and their properties (masses, representations) can be adjusted depending on the case at hand, among other variations. This allows for the study of specific classes of theories to obtain general nonperturbative statements about these theories, for example, studying the N_c dependence in the 't Hooft and/or Veneziano limits. It also allows for LFT studies of specific theories, to investigate, for example, the nonperturbative properties of a given BSM theory.

Conformal field theories (CFT) are broadly interesting in high energy and condensed matter theory. The study of emergent conformal symmetry in Yang-Mills theories coupled to many fermions (*i.e.*, SU(N_c) gauge theories with $N_f \gg 1$ fermions in fundamental or higher representations) is an interesting target of LFT investigations. While identifying the location and order of the expected conformal transition is an ongoing challenge, these studies have yielded phenomenologically and theoretically interesting discoveries. In particular, the existence of a light scalar bound state, which is a possible candidate for a pseudo-dilaton, has been established by several groups, prompting in turn the formulation of dilaton EFT (where such a state would emerge near the conformal transition). These results invite additional nonperturbative studies to further develop the dilaton EFT description. They are of phenomenological interest as potential candidate theories for composite Higgs models, where LHC constraints could be satisfied if the composite Higgs is a pseudo-dilaton or pseudo Goldstone boson. With the development of general purpose tools such as gradient-flow RG, further studies to locate the conformal transition and obtain information about the properties of the emergent CFTs may be feasible yielding results potentially relevant to numerical conformal bootstrap, for example. LFT studies of these and related theories also provide interesting opportunities for BSM phenomenology. LFT results for low energy constants combined with experimental bounds may provide constraints on BSM theory space. Conversely, if strongly favored UV completions are identified, their phenomenology may be obtained from LFT computations.

Composite dark matter models, where the dark sector is described by a (QCD-like) confining theory, are natural targets for LFT studies. Here the methods developed for lattice QCD can be straightforwardly applied to obtain information about the thermodynamics, spectrum, and form factors of the DM particles. The thermodynamics, in particular the nature of the finite-temperature transition of the DM model, affects early-universe cosmology, with the intriguing possibility that a first-order transition could leave an imprint

of primordial gravitational waves. Self-interactions can also be studied with the same methods as developed for hadron-scattering in lattice QCD. Addressing questions such as the dark-matter relic abundance implied by the DM model, while out of reach with current methods, may become feasible with methodological advances.

In summary, studies of relevant LFTs are highly desirable in order to more fully explore and constrain BSM theory space with quantitative information on strongly-coupled QFTs. Indeed, as outlined above, LFT studies of select theories have already yielded very promising results. Interestingly, existing lattice-QCD results obtained at unphysically large up/down-quark masses can be reused in Neutral Naturalness scenarios, where a broken mirror symmetry leads to a QCD-like hidden sector with heavy mirror-quarks. Other potential targets include theories of right-handed neutrinos or composite axions. The large space of theories amenable to LFT computations provides opportunities for exploration, hindered, however, by the high computational cost. Here, theoretical innovations in the theory of ML to efficiently sample configuration space may have transformational impact to alleviate the computational cost. This could enable timely studies of a broad range of relevant LFTs in the coming decade.

Supersymmetry, even if not realized in Nature, is an essential ingredient in the AdS/CFT correspondence and studies of supersymmetric QFTs continue to yield valuable theoretical insights (see Sec. 10.2.1). A recent notable development is a novel lattice formulation of $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) theories which preserves a subset of the full continuum supersymmetry to avoid fine-tuning in the continuum limit. First results from lattice studies in this formulation find good agreement with holography at surprisingly low values of N_c. This opens the door to a whole new area of study with strong synergy with semi-analytic treatments.

10.4.2 Quantum Information

Quantum information has played an increasingly important role in high energy theory research in recent years. Work on the theory of quantum information has yielded new insights into quantum gravity and revealed new structures in certain QFTs. Methods are being developed for quantum computations of QFTs relevant to HEP, offering the intriguing possibility of access to nonperturbative regimes in systems out of reach of classical computation and semi-analytic methods. As discussed in Sec. 10.3.4, theorists are deeply involved in leveraging quantum sensor technology to enable novel experiments.

10.4.2.1 Quantum simulation and quantum computing

Motivated by the limitations of classical computation, recent years have seen a dedicated effort to develop the theoretical formulations, methods, and algorithms to simulate QFT systems on quantum computers as well as analog quantum simulators. The hope is that, as quantum hardware and computational methods mature, it will be possible to employ quantum computations to obtain information about problems such as real-time dynamics of hadron collisions, early universe evolution, the neutron-star equation of state, the nature of QCD phases (including the quark-gluon plasma), SM and BSM theories with chiral fermions or θ terms, axion cosmology, and other systems with sign problems.

The Hamiltonian formulation is a natural choice for quantum simulations, where it is possible to represent the dynamics such that the number of required building blocks (qubits and gates) depend only polynomially on the number of the degrees of freedom. However, the Hilbert space of quantum field theories is infinite-dimensional and must still be truncated in some fashion. In classical lattice field theory simulations

space-time is discretized, while in quantum simulations truncation in field space is also necessary. A number of different digitization schemes have been proposed and are being studied, including Casimir dynamics, conformal truncation, discrete groups, dual variables, light-front quantization, loop-string-hadron formulation, quantum link models, and qubit regularization, among others. The effects of the truncation or digitization schemes need to be carefully studied, particularly for gauge theories, where truncations that break gauge invariance can, in principle, render the theory inconsistent. As a general strategy, truncations that preserve more of the symmetry are favored, as are local encodings of the qubits. After choosing a truncation scheme and encoding the degrees of freedom onto the quantum hardware, the next step is the initial state preparation, formulated in terms of the fields of the theory, followed by time evolution. In the case of digital quantum hardware, the time evolution operator needs to be approximated, for example, via "trotterization", which truncates the infinite series representing the time evolution operator. Efficient quantum algorithms with tightly bounded errors on observables and concrete quantum-computational resource requirements need to be developed for all the relevant problems in high-energy physics, an endeavor that has started in recent years and needs extensive theory input.

In the case of analog quantum simulations, the physical system (for example, cold atoms) and its set-up to control the quantum states are designed to mimic the desired quantum field theory. Each quantum simulator hence represents a dedicated experiment, where the "quantum simulation" requires an initial state preparation and measurements after time evolution. While the space of possible target theories may be limited with a given experimental set-up, analog simulators may be attractive as the experiments can be scaled up to accommodate significantly larger systems which can describe larger Hilbert spaces compared to present-day digital quantum computers.

Tensor network methods, which originated in condensed matter physics, can be used to reformulate lattice gauge theories into fully discrete formulations suitable for Hamiltonian simulation and quantum computation. In one approach, local tensors provide translational invariant building blocks of exact discretizations of the path integral, and encode both the local and global symmetries of the original theory. Symmetry-preserving truncations can then provide controllable finite-dimensional approximations with the same continuum limit as the original theory. In another approach, tensor networks can approximate the wavefunction of a quantum many-body system efficiently, where the dimensionality of the tensors (namely the bond dimension), represents the amount of entanglement retained in the construction of the wavefunction. Hamiltonian dynamics can then be implemented by expressing the operators acting on this tensorial space. Progress in recent years is focused on pushing the developments to higher dimensional and non-Abelian lattice gauge theories. Tensor network constructions can be used to perform classical simulations of quantum circuits, which would yield valuable benchmarks for quantum simulations, crucial tests of the results, and inform aspects such as state preparation.

Given current NISQ (noisy intermediate-scale quantum) era limitations of quantum hardware, theoretical efforts are focused on low-dimensional systems where a variety of different QFTs, including U(1) and SU(2) gauge theories are being studied. Current efforts to understand the best truncation schemes for gauge theories will be very valuable in the future as more powerful quantum computers are being developed. Important tasks for the near-term future include developing the building blocks and optimizing the approximations for NISQ machines. Other potential near-term applications include optimizations for classical computations, for example, of interpolating operator constructions in LFT calculations. The insights gleaned from developing quantum computing methods for QFTs of interest to HEP will also benefit quantum computing in other fields.

10.4.2.2 Fundamental aspects of QIS

The past decade has seen a remarkable convergence of quantum gravity and quantum information, as detailed earlier in this report (see Sec. 10.2). Moreover, quantum information provides a new perspective on quantum field theory. In the consideration of fundamental aspects of quantum information theory, entropy, entanglement, quantum error correction and quantum communication play a prominent role. Unlike traditional explorations of QFTs, information content is used as the organizing principle to better account for the underlying quantum nature of the systems. This has led to the recognition that the structure of entanglement plays a key role in the properties of QFT systems. Quantifying the amount of entanglement to characterize the quantum information depends on the entropic function. Using entanglement entropy in the holographic context reveals a connection between entanglement and geometry, a profound result.

Also significant are the connections that have been revealed between quantum information and nonperturbative structures of QFTs, including irreversability of renormalization group flows, classification of topological phases, implications for dynamics, and progress in understanding the black hole information paradox using holographic entanglement. Information theoretical methods have been used to prove so-called null energy conditions, which place tight constraints on the QFTs. The spread of quantum information in QFTs and other complex systems obeys universal laws and is closely related to transport properties. The study of out-of-time-order correlation functions has yielded insights into scrambling and bounds on the onset of quantum chaos. In short, information theoretic methods applied to QFTs have already yielded important insights, leaving the field wide open for further explorations along themes such as the connections between gauge invariance and information, towards seeking a deeper understanding of the nature of quantum field theory and quantum gravity.

10.5 Community Development

The theory community in the United States is world-leading, a remarkable achievement given the extraordinary level of its international partners. Continuing excellence in research is necessary for maintaining this leadership, but not sufficient; robust support and community development is needed. The United States should emphatically support a broad and balanced program of theoretical research covering the entirety of high-energy physics, from fundamental to phenomenological to computational topics, both in connection to experiment and in its own right. Such support should facilitate the exploration of new research directions, the incorporation of new developments from adjacent fields, and the building of new bridges to gravity, cosmology, astrophysics, quantum information, nuclear physics, AMO, condensed matter physics, statistics, computer science, data science, and mathematics.

The theory community is most effective as part of a balanced HEP program of Projects and Research, as both are essential to the health of the field. Within this balance, support for *people* is vitally important, as they constitute the primary infrastructure of Research endeavors. As such, sustaining the vibrancy of the US theory community requires a concerted effort to support the people that comprise it (especially at early career stages), strengthen the fabric of the community, and broaden participation. Theory contributes an important cultural element within university departments and the broader physics community. Theorists initiate students into the frontiers of particle physics and lead them to fluency in quantum mechanics and field theory, while providing intellectually stimulating environments at their respective institutions. A key goal is to maintain a program across HEP that trains students and junior scientists, providing them with continuing physics opportunities that empower them to contribute to science.

The success of our endeavors depends on "4π" coverage in identifying and cultivating talent at all career stages. To this end, the US theory community (as part of the broader HEP enterprise) would benefit from support to enable the realization of many of the recommendations made in the CEF02 (Career Pipeline and Development in Particle Physics) and CEF03 (Diversity, Equity, and Inclusion in Particle Physics) topical group reports. These include e.g. strengthening support for early career physicists; emphasizing workforce development and reinforcing career pathways in both academia and industry; bringing awareness to the community about different forms of marginalization; creating pathways into the field for members from marginalized backgrounds and providing the support necessary for their success; engaging communities from emerging and developing countries; involving outside experts to help develop strategies for improvement; improving awareness and support for mental health issues; and cultivating work-life balance.

The effectiveness of the theory community as a part of the broader HEP enterprise is enhanced by targeted bridge-building initiatives that connect theory to experiment or to enabling technologies or to both. Past and present examples of such highly-effective initiatives include the LHC Theory Initiative, the LQCD Project, the Neutrino Theory Network, the Muon $g-2$ Theory Initiative, the HEP-QIS QuantISED program, AI for HEP, the Exascale Computing Project, and SciDAC. Support for ongoing and emerging initiatives will strengthen connections to experiment and sharpen focus on key HEP scientific objectives.

10.6 Conclusion

As we enter an era with many promising experiments but few guarantees of discovery, theory is as important as ever. Theory unifies the frontiers of particle physics. It is essential to the conception, execution, and interpretation of current experiments. Theory is an essential driver of the development and implementation of new, enabling technologies. It also extends well beyond by laying the foundations for future experiments and advancing our understanding of Nature in regimes that experiment has yet to reach. A robust theory program is vital to the success of current and future Projects in particle physics.

As summarized in this report, the past decade has seen remarkable (and deeply interconnected) progress across all facets of high-energy theory, from fundamental theory to phenomenology to computational theory. This progress — alongside rapid developments at the accelerator and the computational frontiers; data from myriad experiments at the cosmic, energy, neutrino, and rare and precision frontiers; and convergence with other fields of physics — has contributed greatly to the advancement of particle physics and laid the groundwork for a coming decade of immense promise.

The theory community in the United States has been central to the recent developments discussed in this report and is poised to play a leading role in the years to come. Such leadership is invaluable and cannot be taken for granted. We do not know what Nature has in store for us. We will be in the best position to realize the immense promise of the coming decade with strong and sustained support for all aspects of theory, both in relation to Projects and in its own right.

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11

Underground Facilitiies and Infrastructure Frontier

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Executive Summary

From the properties and nature of the neutrino to the direct measurement of galactic halo dark matter, research performed at underground facilities tackles a collection of precision knowledge of the constituents of the Standard Model of particle physics to broadly open-ended search well Beyond the Standard Model (BSM). The chapters and reports from other Frontiers layout the science case for these and other avenues of particle physics research. Here we identify the needs and requirements for underground facilities continue to support the breadth of particle physics research planned in the coming 10–15 years.

Our overall evaluation begins with assessment starting with the Underground Laboratory Capabilities report from Snowmass 2013 [1] and those 2014 P5 report [2] recommendations relating to science performed in underground facilities. The Snowmass report conclusions included locating LBNF/DUNE at the Sanford Underground Research Facility, pursue continued leadership in dark matter and neutrinoless double-beta decay, coordinate with overseas and domestic underground facilities to ensure a position of leadership, and maintain a domestic underground facility to support current and future generations of largest dark matter and neutrinoless double-beta decay experiments. The 2014 P5 report recommended proceeding with LBNF/DUNE in the U.S., launch the Generation 2 dark matter direct detection program, and then plan and initiate a follow-on Generation 3 dark matter direct detection program.

The underground facilities and infrastructure Topical groups assessed the requirements in the areas of neutrino, cosmic frontier, supporting capabilities, synergistic, non-high energy physics research also performed in underground facilities, and an assessment of current status of underground facilities world-wide. While numerous observations resulted, several key observations set the framework for planning for the next decade of science at underground facilities:

- The LBNF/DUNE program of neutrino science will be the flagship U.S. high energy physics research effort for the coming decade and beyond. This program hinges on success at the Sanford Underground Research Facility (SURF).

- The long-term underground infrastructure investment at SURF creates opportunity for complementary and synergistic research, both within the high energy physics community and beyond.
- The current programs of dark matter direct detection will culminate in the late 2020s and planning for next generation dark matter research should begin in this Snowmass period to ensure the underground facilities and infrastructure are available and ready.
- While much of the required expertise and infrastructure for future underground high energy physics research is well developed, current underground facilities are fully subscribed with existing or planned experiments. New space (excavation) is likely required to support the programs of research for the coming decade and beyond.

From the above assessments, the primary conclusions of the Underground Facilities and Infrastructure evaluation are:

UF #1: Leverage the Long Baseline Neutrino Facility excavation enterprise to increase underground space at Sanford Underground Research Facility in a timely and cost-effective way to permit siting of next-generation underground high energy physics research experiments.

UF #2: Designate the Sanford Underground Research Facility as a U.S. Department of Energy User Facility.

UF #3: Provide full support for the underground facilities hosting the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

UF #4: Following the 2014 P5 Recommendation 20, R&D and decision making for a third-generation direct detection dark matter program should commence immediately to enable a construction start in the late 2020s.

UF #5: To ensure a robust collection of scientific programs in underground facilities, support the enabling capabilities, technique development, and expertise required for underground experiments.

Within the full report below of from the Underground Facilities and Infrastructure Frontier, each of these conclusions is explained in context and presented in greater detail.

11.1 Introduction

The decade since Snowmass 2013 has seen extraordinary progress of high energy physics research performed–or planned for–at underground facilities. Drs. T. Kajita and A.B. McDonald were awarded the 2015 Nobel Prize in Physics for the discovery of neutrino oscillation [3], which show that neutrinos have mass. The U.S. has embarked on the development of the world-class LBNF/DUNE science program to investigate neutrino properties. The Generation 2 dark matter program is advancing to full data collection in the coming ∼5 years, a Dark Matter New Initiatives program has begun, and the U.S. dark matter community is looking toward a Generation 3 program of large-scale dark matter direct detection searches. The Sanford Underground Research Facility has become a focal point for U.S. underground facilities and infrastructure investment. Here we briefly review the status as was seen by those who participated in the 2013 Snowmass process as well as the outcome from the 2014 P5 program of recommendations.

11.1.1 Taking stock of Snowmass 2013

The Underground Laboratory Capabilities report from Snowmass 2013 [1] outlines plans, needs, and concerns contemporary at that time. Here we briefly take stock of what has been accomplished in view of the four main conclusions provided by the Underground Laboratory Capabilities report.

1. Locate LBNE underground to realize its full science potential. This step would also provide a natural base for additional domestic underground capabilities at SURF in the future.

2. The U.S. has leading roles in many of the future dark matter, neutrinoless double beta decay and neutrino experiments.

3. More coordination and planning of underground facilities (overseas and domestic) is required to maintain this leading role, including use of existing U.S. infrastructure and closer coordination with SNOLAB as the deepest North American Lab.

4. Maintaining an underground facility that can be expanded to house the largest dark matter and neutrinoless double beta decay experiments would guarantee the ability of the U.S. to continue its strong role in the worldwide program of underground physics.

Since Snowmass 2013, LBNE has been split into the Long Baseline Neutrino Facility (LBNF) which provides the neutrino beam and facility complex and the Deep Underground Neutrino Experiment (DUNE) which is the suite of detector modules used to study neutrino properties [4–7]. Effectively, the first item is being fulfilled through the construction of LBNF and DUNE.

The second conclusion item is written as an observation, but largely remains true today. The DOE Office of High Energy Physics has directly supported the construction of two second-generation (G2) direct detection dark matter experiments located in underground facilities. The LZ experiment [8], located at the Sanford Underground Research Facility (SURF), has recently reported initial and world leading results [9]. The SuperCDMS experiment [10], located at SNOLAB, is under construction with data collection expected to commence in 2023. The DOE Office of Nuclear Physics has recently announced the intent to develop three world-leading, ton-scale neutrinoless double-beta decay experiments (i.e., CUPID [11], LEGEND-1000 [12], and nEXO [13]). As described above, LBNF/DUNE will become a world-leading effort in neutrino physics experiments.

Over the last decade, the U.S. has maintained its leadership role in the targeted underground research areas of "dark matter, neutrinoless double beta decay and neutrino experiments". Since the writing of the 2013 Snowmass reports SURF and SNOLAB have developed into world-recognized peers in underground science. Both of these underground facilities, as observed through the 2021–2022 Snowmass process, are operating "at capacity" with current and near-term planned experiments.

The fourth item is only partially complete. As just previously stated, SURF is operating "at capacity" with current and near-term planned experiments. However, expansion of SURF underground space would make the theme of the fourth item feasible on an appropriate time-scale (mid- to late-2020s) to fulfill the fourth conclusion.

11.1.2 Progress since the 2014 P5 report

The 2014 P5 report [2] contained three recommendations relevant to assessing underground facilities and infrastructure:

> **Recommendation 13:** Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.
>
> **Recommendation 19:** Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.
>
> **Recommendation 20:** Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. Seek a globally complementary program and increased international partnership in G3 experiments.

As described above, the LBNF/DUNE and the G2 dark matter programs are underway and largely fulfill **Recommendation 13** and **Recommendation 19**. However, **Recommendation 20** is at best in a nascent state.

11.2 Key Observations from Underground Facilities & Infrastructure Topical Reports

In additional to the assessment described above of the progress since Snowmass 2013 and the 2014 P5 report, the 2021–2022 Snowmass process has freshly assessed the status needs for underground facilities and infrastructure to support the science goals of the next decade and beyond. In this section we briefly summarize the key observations stemming from the assessments performed by the Topical groups within the Underground Facilities and Infrastructure Frontier.

11.2.1 Key Observations – Underground Facilities for Neutrinos

The LBNF/DUNE program is a key, flagship high energy physics research program relying on underground facilities and infrastructure. Notably the Sanford Underground Research Facility (SURF), where potions of LBNF/DUNE are located, is where all major U.S. investments in underground facilities and infrastructure have been made over the last 10 years.

The underground cavern space provided by LBNF will soon complete. The timeline for Phase II of DUNE is not yet decided, but likely initiates in the 2030 or later time frame. There are several potential scenarios for underground space utilization in advance of the completion of DUNE via Phase II construction.

Proposals for future large-scale detectors targeting measurement of natural neutrino sources (*e.g.*, supernova, solar, geoneutrinos, ...) which, if pursued, will require large underground spaces which are not currently available in the suite of existing underground labs.

Future neutrinoless double-beta decay experiments, supported by nuclear physics programs, are expected to require underground facility space and infrastructure in the coming decade and beyond. It remains an open question whether deeper experimental locations are required for future neutrinoless double-beta decay experiments.

The full Underground Facilities for Neutrinos (UF1) topical report is available [14].

11.2.2 Key Observations – Underground Facilities for the Cosmic Frontier

Multiple new underground dark matter experiments are expected and being planned (at both large and small scales). At the same time, underground facilities are largely subscribed by existing projects, with only very limited space available in the coming years. There is, then, a clear need for additional underground space, tailored to the needs of dark matter experiments.

This underground space should specifically include both large spaces for large experiments (liquid noble) and small spaces for smaller experiments (cryogenic bolometer, 'other'). The assembly of large liquid noble experiments will occur largely in the underground environment, meaning they require large underground radon-free clean rooms. Given the volume of gas/cryogen, such experiments also require large underground areas for staging (e.g., gas storage) and experiment utilities (e.g. pumps, distillation).

These new suitable spaces must be available by the late 2020's to meet the demand. This demand may be met in North America by proposed new excavations at SURF or SNOLAB.

The full Underground Facilities for the Cosmic Frontier (UF2) topical report is available [15].

11.2.3 Key Observations – Supporting Capabilities for Underground Science

Future, larger experiments will increasingly require underground assembly with stricter radioactivity requirements. There will need to be larger, cleaner cleanrooms, often with better radon-reduction systems and increased monitoring capabilities for ambient contaminants. Methods to assay dust deposition and radon-daughter plate-out will need to be improved. There will be increased need for underground machine shops. Additionally, many labs are considering adding underground copper electroforming to mitigate against cosmogenic activation, as has been successfully demonstrated at SURF.

Most assay needs may be met by existing worldwide capabilities with organized cooperation between facilities and experiments. Improved assay sensitivity is needed for assays of bulk and surface radioactivity for some materials for some experiments, and would be highly beneficial for radon emanation.

The full Supporting Capabilities for Underground Facilities (UF4) topical report is available [16].

11.2.4 Key Observations – Synergistic Research in Underground Facilities

A variety of research beyond high energy physics is performed in underground laboratories. These research activities from other disciplines include burgeoning R&D in quantum information science, accelerator-

based nuclear astrophysics, tests of fundamental symmetries, gravitational wave detection, and geology & geophysics.

In most all cases, research groups from differing disciplines are able to work in shared underground facility space harmoniously and in some cases synergistically. Smaller-scale research efforts benefit substantially from the investment in underground facilities and infrastructure initially prepared for larger-scale science endeavors.

Evaluating the "total research impact" of shared-usage underground research facilities should take into account the full disciplinary breadth of research performed.

The full Synergistic Research in Underground Facilities (UF5) topical report is available [17].

11.2.5 Key Observations – Underground Facilities & Infrastructure Overview

The 2022 Snowmass process documents an increasing demand for the special environments provided by deep underground laboratories to conduct high priority science. Emergent applications have been identified beyond neutrinos and dark matter searches, expanding the demand across more HEP frontiers including quantum information science (QIS), quantum computing (QC), and atom interferometry. The 2014 P5 report established several high priorities for high energy physics including a domestic G3 direct detection dark matter effort and LBNF/DUNE. The intervening years have witnessed a rapid growth in new technologies for a variety of HEP topics which are rapidly approaching prototype phases. Some of these are a result of Dark Matter New Initiatives (DMNI) and Basic Research Needs (BRN) for High Energy Physics Detector Research & Development efforts.

11.2.5.1 Underground laboratories

As part of Underground Facilities Frontier the major underground laboratories (see Fig. 11-1) were assessed for their current capacity to support science, current expansion efforts, and plans for future expansions. These are summarized in Table 11-1. The analysis identifies that most facilities have existing capacity to host small scale efforts including R&D deployments and prototype experiments. Two facilities are expanding their facilities to accommodate long baseline neutrinos - LBNF/DUNE at SURF [18] and Hyper-Kamiokande at Kamioka [19]. SNOLAB is reserving a significant cavity for neutrinoless double-beta decay and INFN-Gran Sasso is expanding their double-beta decay suite of experiments. The three Office of Nuclear Physics supported efforts, nEXO, LEGEND, and CUPID are in discussion or developing plans to utilize these facilities, lacking a domestic option for hosting these efforts with significant U.S. participation or leadership. The U.S. underground facility, SURF, does not have capacity to host a Generation 3 direct detection dark matter experiment. Of the facilities surveyed by the Underground Facilities and Infrastructure group, LNGS and SNOLAB will have space opening following decommissioning of existing experiments. At the time of the Snowmass meeting in Seattle (July 2022), no Generation 3 experimental collaboration had assessed or selected an underground location.

11.2.5.2 Future underground laboratory capacity

During the Snowmass process proposals were presented for expanding three laboratories to create adequate capacity for a G3 experiment. These are SURF(U.S.), SNOLAB(Canada), and Boulby(UK). All three

11.2 Key Observations from Underground Facilities & Infrastructure Topical Reports

Facility	Depth (m.w.e.)	Current science program	Expansions underway	Capacity for small scale experiments	Capacity for G3 DM or tonne scale DBD	Proposals for future expansion
Boulby	2850	CYGNUS, Low Background Assay, NEWS-G/ Dark Sphere R&D		modest	none	∼30 m diameter cavity for G3 DM. Potentially deeper location.
Kamioka	2700	SuperK, T2K, KamLAND-Ze, CLIO, KAGRA, NEWAGE, CANDLES, Hyper-K	Hyper-K	modest	none	
LNGS*	3600–3800	COBRA, COSINUS, CRESST, CUORE, CUPID-0, CUPID, DAMA, DARKSIDE, ERMES, GERDA, GINGER, LUNA, LVD, NEWS-DM, SABRE, VIP, XENON		modest	Decommissioning of Borexino, CTF, and DarkSide 50 (∼20x20 m^2) creates a large enough space for a G3 DM experiment.	
Sanford Underground Research Facility (SURF)	4200	LZ (DM), MJ-^{180}Ta, CASPAR, Low Background Assay, Geomicrobiology, Geoengineering, Education & Outreach, LBNF/DUNE	LBNF and DUNE	limited	none	100 m lab module(s)
SNOLAB	6000	SNO+(LS), PICO 40, CUTE, SENSEI, OSCURA, DAMIC, HALO, SuperCDMS, SNO+(LS), DEAP-3600 II, PICO-500, ECUME, NEWS-G, SNO+(Te), SBC		modest	Decommissioning Cube hall projects creates a 18x15 m space for G3 DM or tonne-scale DBD.	
Yemilab	2500	LSC, AMoRE, COSINE, KNU, KIGAM, IsoDAR		limited	none	

Table 11-1. *Tabulation of key details of underground laboratories. A key focus is given to Generation 3 dark matter (G3 DM) and tonne-scale neutrinoless double-beta decay (tonne-scale DBD) as these classes of experiments have similar large space and infrastructure requirements. Depth is given in units of meters of water equivalent (m.w.e). * LNGS did not return the Snowmass UF questionnaire, however the September 2022 LNGS Science Committee report suggests availability of the Borexino and DarkSide spaces in Hall C. The assessment of available space for small scale experiments was approximately gauged by the metric: limited ∼≤100 m^2 and moderate between ∼100 and ∼500 m^2.*

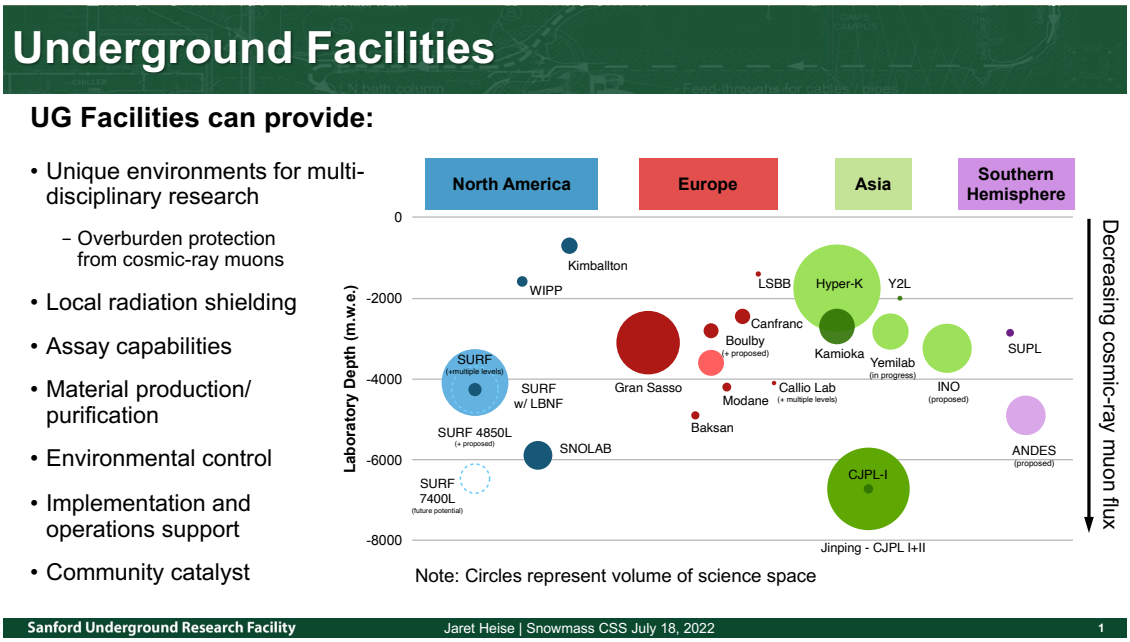

Figure 11-1. *Overview of underground facilities located around the world, showing various key characteristics in depth and underground laboratory capacity. Slide from Jaret Heise (SURF).*

proposals would be adequate for supporting a G3 program. The SURF proposal would provide space and capacity beyond those required by this one experiment. The alternative off-shoring U.S. scientific efforts creates the potential for negative impacts on U.S. scientific leadership, technology development, and while increasing costs and adding challenges to the U.S. science. This was a recurring theme of discussions during Snowmass. Pressure on the U.S. research budgets are amplified as a consequence of the significant travel costs and any international travel restrictions (e.g., COVID, etc.).

The SURF proposal is presented in the figure below. Two locations for multiple laboratory modules have been developed near the Ross Campus, the site of current LBNF/DUNE excavations. Excavation of these modules could utilize the significant infrastructure investments from the DUNE excavation to create these spaces. Coordinating the lab modules with the DUNE contracts could result in very significant cost and schedule saving by reducing or eliminating mobilization and demobilization costs, O($15M). A long term option for a deeper campus is also shown, though it was generally not considered as part of planning "for the next Snowmass period". Nevertheless, the deep lab option provides potentially opportunity for future growth should the scientific community's goal require increased shielding from cosmic ray secondaries.

The South Dakota Science and Technology Authority presented in their Snowmass whitepaper these conceptual plans and their intention to pursue State and Private funding for the excavation for one module. With appropriate coordination the 100 m laboratory module would be ready for Beneficial Occupancy on a relevant timescale. This would provide adequate space for a Generation 3 dark matter experiment, another large-scale experiment such as neutrinoless double-beta, or multiple smaller scale R&D projects or pathfinder experiments.

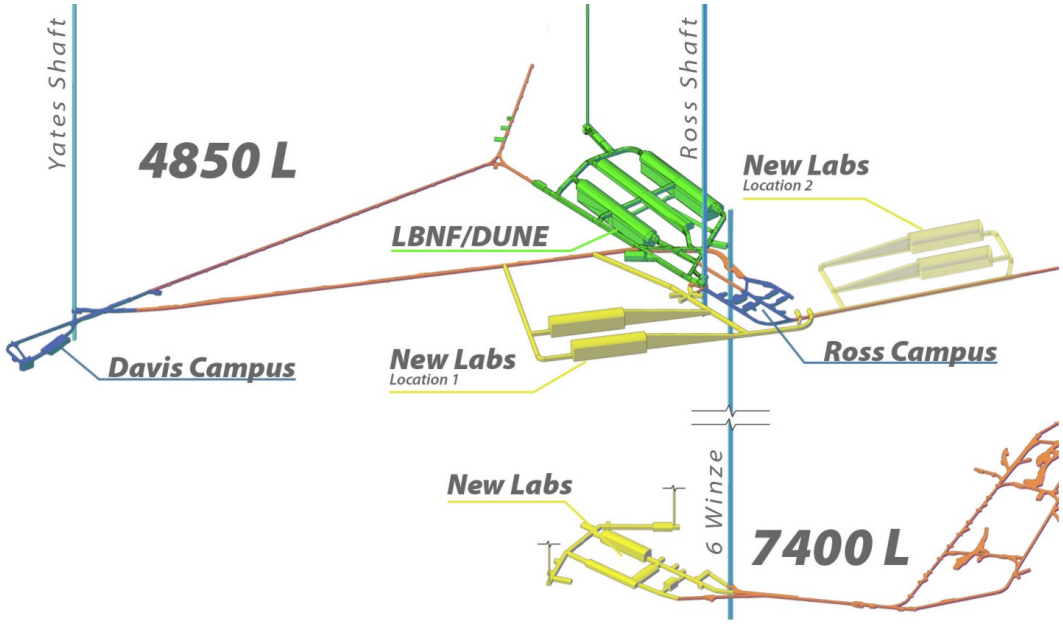

Figure 11-2. *SURF expansion plan, with new labs labeled and shown in yellow. Graphic from Jaret Heise (SURF).*

11.3 A U.S. strategy for underground facilities – Conclusions

The Underground Facilities and Infrastructure Frontier was charged to "develop a integrated strategy for underground facilities in the coming decade and beyond". A strategy requires a set of actionable steps. Thus, we frame the proposed strategy as a set of actionable conclusions, with clear steps for implementation, that will lead to outcomes substantially advancing and supporting the long-term vitality, capacity, and leadership potential of the U.S. high energy physics community to perform research requiring underground facilities. Each of the following actionable conclusions is intended to lead to positive outcomes taken alone, but the full implementation of all actionable conclusions taken together amplifies the impact as the set is interrelated, self-consistent, complementary, and mutually supporting.

11.3.1 UF Conclusion #1: Excavate now for future experiments

Evaluations from the Snowmass Underground Facilities and Infrastructure Frontier's efforts drew a conclusion that today's underground facilities are currently full to capacity with current and planned experiments. More underground space is required for the research planned for the late 2020s and beyond. The mobilization cost for underground excavation is on the order of a small-to-mid-scale experiment (tens of million USD). Acting now to extend excavation at SURF can cost-effectively provide the necessary space to fulfill the science objectives of the Neutrino and Cosmic Frontiers in the coming decade and beyond.

UF Conclusion #1: Leverage the Long Baseline Neutrino Facility excavation enterprise to increase underground space at Sanford Underground Research Facility

in a timely and cost-effective way to permit siting of next-generation underground high energy physics research experiments.

The high energy physics community is planning to pursue both large- and small-to-mid-scale underground searches for the direct detection of particle-like dark matter. A large-scale liquid noble dark matter experiment will require a host cavern on the $25\times25\times25$ m^3 size, ready and available on the time scale of the late 2020s. Small-to-mid-scale dark matter experiments, for instance those part of the U.S. DOE Office of High Energy Physics' Dark Matter New Initiative efforts, would benefit from outfitted cavern drifts able to support multiple experiments, ready and available on the time scale of the mid-2020s. The excavations required for these effort are comparable to a single module of the Long Baseline Neutrino Facility.

Connecting to UF Conclusion #2, the designation of SURF as a U.S. DOE User Facility is not fully realized and does not provide utility to the broader scientific community *unless* space for research is ready, outfitted, and organized under an appropriate managing institutional structure.

11.3.2 UF Conclusion #2: U.S. Underground User Facility

The Sanford Underground Research Facility (SURF) is both the single largest underground science-oriented facility in the U.S. supporting high energy physics and the location of the current largest U.S. investment in infrastructure for long-baseline neutrino detection. Furthermore, SURF hosts dark matter and neutrinoless double-beta decay experiments, both seeking to probe physics beyond the Standard Model. Finally, SURF has provided space and support for a range of other research from accelerator-based nuclear astrophysics to geoengineering. Future users may include quantum information science (QIS) researchers, atom interferometry gravitational wave detection, and/or biological science.

UF Conclusion #2: Designate the Sanford Underground Research Facility as a U.S. Department of Energy User Facility.

The U.S. Department of Energy's Office of Science manages a formal process for the designation of a user facility: "A user facility is a federally sponsored research facility available for external use to advance scientific or technical knowledge..." meeting a number of conditions. Designation of SURF as a user facility would provide the high energy physics community a clear structure for seeking hosted underground space and infrastructure use agreements that will accelerate the research community's ability to plan and conduct next-generation experiments requiring underground locations. A list of existing DOE Office of Science user facilities [20] is available as well as the process and definition [21] for creation of such user facilities.

11.3.3 UF Conclusion #3: Support completion of LBNF and DUNE

As described by Lia Merminga, Director of Fermi National Accelerator Laboratory, the U.S. will soon host the world's most capable neutrino experiment composed of the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE). To ensure success of this flagship U.S. high energy physics program in long-baseline neutrino research for the coming two decades, the following conclusion is made:

UF Conclusion #3: Provide full support for the underground facilities hosting the Long Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

The program of research pursued by LBNF and DUNE is central to the Snowmass Neutrino Frontier's vision for scientific discovery in the coming two decades. Organizational and infrastructure support for the hosting underground facility during this time period is a key component to ensuring this flagship U.S. high energy physics research program delivers. Achieving the full scientific reach of this long-baseline neutrino research program will require completion of all four planned DUNE modules, an investment in discovery science reaching into the 2030s time period.

Additionally, connecting to UF Conclusions #1 and #2, the excavation of space and designation of SURF as a U.S. DOE User Facility, respectively, provides an integrated means for evaluating, managing, and overseeing any proposed beneficial utilization of the LBNF caverns in advance of the full and complete installation of DUNE modules 3 and 4 in the 2030s.

11.3.4 UF Conclusion #4: Realize the 2014 P5 Recommendation for G3 dark matter

In 2021–2022, the Snowmass Cosmic Frontier continues to place high priority on the search for dark matter. In this respect, the 2014 Particle Physics Project Prioritization Panel (P5) Recommendation 20 is yet unfulfilled. The full supporting text of the 2014 P5 Recommendation 20 is:

> *"The results of G2 direct detection experiments and other contemporaneous dark matter searches will guide the technology and design of third-generation experiments. As the scale of these experiments grows to increase sensitivity, the experimental challenge of direct detection will still require complementary experimental techniques, and international cooperation will be warranted. The U.S. should host at least one of the third-generation experiments in this complementary global suite.*
>
> ***Recommendation 20: Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. Seek a globally complementary program and increased international partnership in G3 experiments."***

Considering the Cosmic Frontier's continued priorities requiring underground facilities, and the 2014 P5 Recommendation 20, the following conclusion is made:

UF Conclusion #4: Following the 2014 P5 Recommendation 20, R&D and decision making for a third-generation direct detection dark matter program should commence immediately to enable a construction start in the late 2020s.

This conclusion drives the planning and decision making process that will determine the underground facility and infrastructure requirements to support experiments of these scales. As the third-generation particle-like dark matter program is projecting construction start in the late 2020s, the preceding development of underground facilities and infrastructure must begin now.

UF Conclusion #4 is highly synergistic with UF Conclusion #1, but UF Conclusion #4 must be pursued of its own accord to ensure the search for particle-like dark matter, one of the Cosmic Frontier's highest priorities is ready to progress in the late 2020s and into the 2030s time period.

11.3.5 UF Conclusion #5: Support underground researchers and R&D

The nature and maturity of high energy physics research performed in underground facilities is reaching a point of becoming *generational*, where experiments are planed, constructed, and performed over multiple-decade time scales. A diverse and inclusive workforce educated, skilled, and active in the development of the tools and techniques used in underground high energy physics experiments is necessary to carry these experiments through to completion.

> **UF Conclusion #5: To ensure a robust collection of scientific programs in underground facilities, support the enabling capabilities, technique development, and expertise required for underground experiments.**

This conclusion is focused on ensuring research funding support is available to train the next-generation of underground researchers through experiential mentoring from today's underground scientific experts. In addition to the construction of major projects, small-scale R&D programs to support advances in techniques and capabilities supporting underground science are a critical component of maintaining the field and educating the next generation.

UF Conclusion #5 undergirds the other UF Conclusions #1 through #4, for underground facilities and infrastructure are nothing without the researchers who invest their effort and careers in the discovery science that is only possible when performed below the Earth's surface.

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12

Snowmass Early Career

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Executive Summary

Early career members of the HEPA community are a distinct population with a particular vision, perspective, and set of accompanying challenges that differ from those of the senior members of the field. Whether early career is defined as students and post-doctoral-equivalent stages or it includes faculty in their early career, what they have in common is a lower, often more vulnerable position in the hierarchy of our field. This, coupled with the fact that they are the source of a majority of the labor of our research, makes them placed to both uniquely contribute to and be affected by the direction of the field in the coming decade.

The definition of early career used for this document is "people within 10 years of their most recent degree with time allowance for any long-term leave from the field". In practice, an overwhelming majority of the participants in the SEC group and those identifying with the term Early Career are at a graduate or post-graduate (e.g. postdoc) equivalent career stage.

The early career community has made significant strides in broadening representation in HEPA since the last Snowmass process, particularly in their efforts to start and expand the reach of Early-Career Organizations (ECOs) within experimental collaborations and at national labs. These ECOs have played significant roles to identify the issues that are especially relevant to this community, and they have made substantial contributions to the betterment of our scientific reach as a community throughout the years.

The genesis of SEC for Snowmass 2021 came from a broadly distributed call for interest that returned over 250 responses. The organization was built to be fully inclusive, such that anyone who wanted to participate could do so. The definition of "early career" (EC) that was adopted covered anyone with ten years of receiving their highest degree, with flexibility on this number to accommodate nontraditional career paths or breaks. This also was chosen to include technicians, engineers, and other members of the physics community that are not PhD holders. Ultimately, a large majority of SEC participants were students and postdocs. The current and previous Early Career members of the Division of Particles and Fields (DPF) Executive Committee were tasked with contributing to the leadership of this organization, ensuring close ties and clear communication with the organizing unit.

Personpower then organically separated into two parallel groups, the structure of which is shown diagrammatically in Figure 12-1 and described in the text below. The first was referred to as Snowmass Coordination, and consisted of liaisons to each frontier of the Snowmass structure. Its goal was to connect early career (EC) physicists to projects within their frontiers of interest. Liaisons had the responsibility

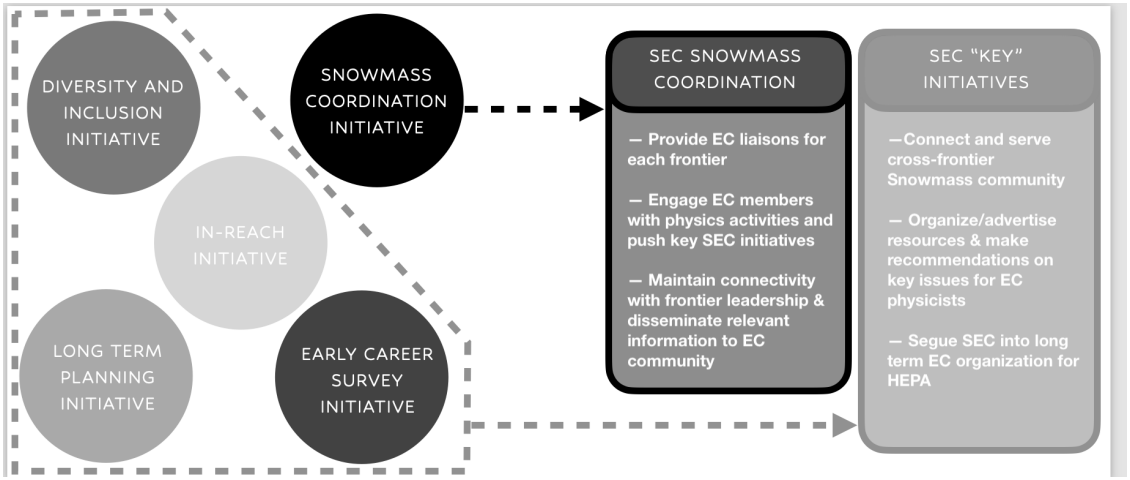

Figure 12-1. *Organization of SEC. Left: The SEC sub-groups or initiatives, corresponding to spheres of early career interest. Right: Organizational division and development of "Key" or "Core" initiatives.*

of attending frontier-level meetings and representing the interests of the EC community. Each frontier organized its liaison structure differently, depending on the number of candidates interested in a liaison position. The most common model was 1-3 liaisons with staggered rotating leadership to provide continuity while lessening the leadership commitment.

The second pillar of SEC was the Core Initiatives Organization, which gathered community input on the topics of greatest importance to EC scientists and set up subgroups dedicated to each. The four topics covered were Inreach, focusing on peer networking and connectivity among EC community members; Diversity, Equity & Inclusion (DEI); Survey, to obtain up-to-date data on community opinions and perspectives; and Long-Term Organization, to discuss sustainability of the effort. The activities of these subgroups included the organization of informational panels and colloquia and the generation of recommendations for the general Snowmass management. The SEC-organized community-wide survey is one of the main P5-relevant works to come from the SEC organization, and includes information on careers, physics outlook, workplace culture, and US visa policies. The survey results are documented in detail in an associated white paper [1]. The key takeaways and recommendations from the SEC Survey are summarized in Section 12.2.

More details on the creation and structure of the SEC organization can be found in a dedicated white paper [2]. This process elapsed over nearly two years due to delays from the COVID-19 pandemic, and the effect of this on efficacy and connectivity is discussed in the white paper.

Through the Snowmass process, we developed a number of recommendations with input from the early career community. Below we give a top-level summary of these recommendations. More detailed recommendations and their motivations are described in detail in the remainder of this chapter.

1. Institutions, experiments, and funding agencies should increase their commitment to adding and maintaining early career representation in decision-making bodies at all levels (e.g. review and advisory panels, governing bodies, etc.) and foster the development of early career organizations.

2. Institutions and funding agencies should address the need for economic equity for early career scientists by increasing the pay of early career positions to match industry equivalents and providing funds for improving meeting accessibility.

3. Funding agencies, experiments, and institutions should restructure the processes for reporting and investigation of discrimination and harassment to ensure true accountability and to robustly support equity, diversity, and inclusion in the field.

4. Career development and community efforts like outreach, mentoring, and advocacy should be recognized by institutions and funding agencies as critical tasks to the scientific output and health of the field. Institutions and funding agencies should provide support for service efforts, include this work in job expectations, ensure that faculty and scientists are given adequate time and credit for this work, and ensure that service work is equitably distributed.

5. Institutions should track career outcomes and adequately train early career scientists to move into a variety of job sectors, especially industry positions, through providing professional development opportunities, creating networking opportunities, and exposing early career scientists to a larger diversity of job sectors and mentors.

6. Institutions and funding agencies should continually examine and adapt their policies to address changing trends in HEPA, including changing job expectations, flexibility in remote work, and increasing competition in both the job market and funding opportunities.

7. Institutions and funding agencies should improve support for scientists with caregiving responsibilities, including encouraging reasonable work hours, providing adequate salaries, offering paid Medical and Family leave to all employees and supporting employees who use it, subsidizing or offering childcare, and fairly evaluating caregivers' drop in productivity in the context of current events of broad impact (e.g. COVID-19) in hiring and promotion committees.

8. Institutions and funding agencies should evaluate and assess the impacts of the COVID-19 pandemic over the coming years and adapt policy to support those most affected by COVID-19 and future events of similarly broad impact.

9. Institutions should provide comprehensive support to early career scientists, including resources, protections, and policies to support a healthy workplace culture and mental health

10. Institutions and funding agencies should take steps to improve U.S. visa and immigration policies by implementing more inclusive hiring processes as well as advocating for updated policies and streamlined application processes for scientists and STEM professionals.

12.1 Introduction

The Snowmass 2021 strategic planning process provided an essential opportunity for the United States high energy physics and astroparticle (HEPA) community to come together and discuss upcoming physics goals and experiments. As this forward-looking perspective on the field often reaches far enough into the future to surpass the timescale of a single career, consideration of the next generation of physicists is crucial.

The 2021 Snowmass Early Career (SEC) organization aimed to unite this group, with the purpose of both educating the newest generation of physicists while informing the senior generation of their interests and opinions. SEC is the latest in a series of the previously dubbed "Snowmass Young" organizations, from 2013 [3] and 2001 [4]. This iteration has expanded on these efforts to significantly increase involvement and broaden the representation of the early career community in the process.

Early career physicists are the future of the field. They will design, build, and operate next-generation experiments and usher in new discoveries. They are also disproportionately involved in work to develop an inclusive climate within HEPA. This document summarizes the work of SEC in consolidating a huge variety of physics perspectives and community opinions towards a bright, strategic future.

12.2 SEC Survey Report

The Snowmass Community Survey was designed by the Snowmass Early Career (SEC) Survey Core Initiative team between April 2020 and June 2021 with the aim of collecting demographic, career, physics outlook, and workplace culture data on a large segment of the Snowmass community. The team reviewed questions from past Snowmass surveys, developed new topics, and came to a consensus on the survey questions. The survey was released to the community on June 28, 2021 and had nearly 1500 total interactions before it closed on August 26, 2021. This section summarizes the key findings and recommendations from the SEC survey. Most of the text in this section has been excerpted and paraphrased from the SEC survey report [1] with permission from the authors.

The survey was distributed broadly via: the Snowmass Slack and email; an article in Fermilab At Work [5]; an email to the Fermilab users list; collaboration spokespeople to their collaboration members; the July 2021 DPF newsletter [6]; and advertisements on software forums (e.g. Geant4 and ROOT), American Physical Society (APS) forums, and social media sites (e.g. Reddit [7]). Qualtrics fraud detection features were used to detect duplicate submissions and screen for bots [8] [1].

The survey questions broadly fall into seven categories: demographics, physics outlook, careers, workplace culture, diversity and racism, caregiving responsibilities, and the impacts of COVID-19. Figure 12-2 shows the outline of the 2021 Snowmass Community Survey. The survey was implemented using online Qualtrics [9] software hosted by Duke University, which enabled using display logic to ask unique sets of questions to different groups of respondents (represented by the brackets in Fig. 12-2). Additionally, all questions except the first question ("Are you currently in academia?") were optional, so questions did not have a set number of respondents. A majority of the physics outlook questions were only shown to respondents who answered that they were currently in academia.

Several measures were taken in the analysis to protect the respondents' privacy, including removing raw response numbers and re-normalizing distributions for all non-demographic results, only showing category

[1] No submissions were tagged as duplicate. A few survey interactions were flagged as potential bots, but they were found to contain logical responses and comments and thus were not removed.

breakdowns with ≥ 5 responses in figures, and only separating responses based on provided demographic information into groupings with at least 30 responses.

There were 1462 total interactions with the survey. The survey team limited the number of respondents to those that reached the end of (or continued beyond) the first section, which contained career-related questions. This reduced the total number of respondents to 1014.

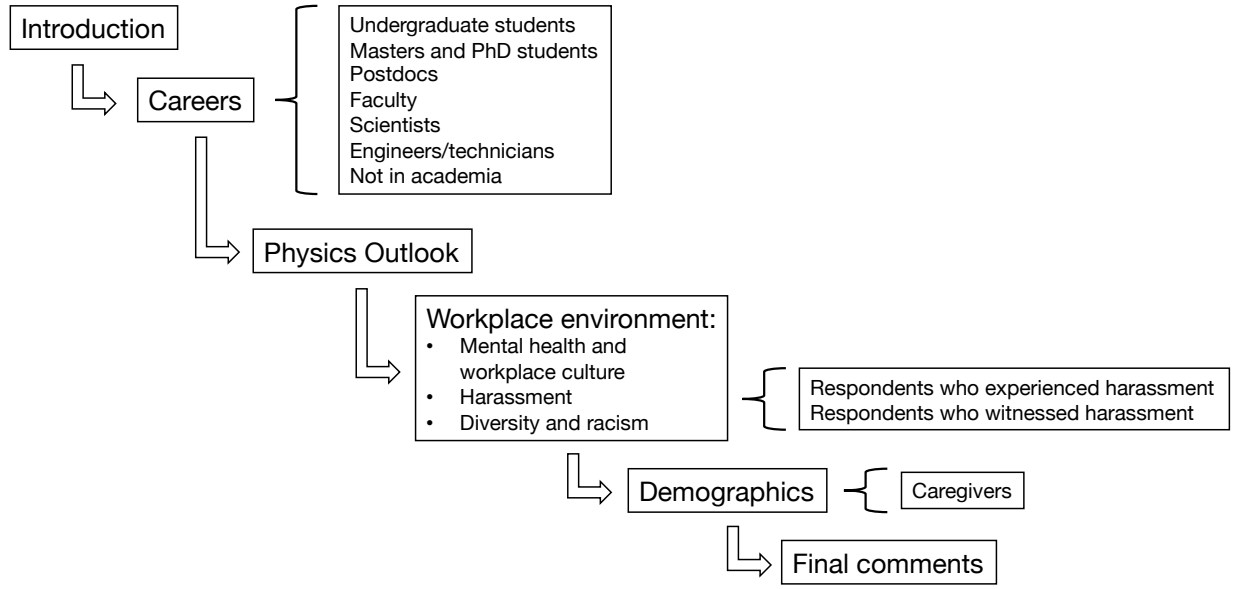

Figure 12-2. *General overview of the 2021 Snowmass Community Survey. The arrows represent the overall flow of the survey ordered by the questions respondents viewed earliest, and the brackets present some of the display logic utilized in the survey.*

Here we present a high level summary of the key findings and recommendations from the survey report. The full analysis and additional findings are available in the full survey report [1]. Section 12.2.1 summarizes the key findings on physics outlook from the survey respondents, while Section 12.2.2 discusses the key findings and recommendations of the other survey sections.

12.2.1 Physics Outlook

The survey responses demonstrate broad interest and participation across all of the different Frontiers, with a significant number of respondents indicating that they had interests outside their particular research focus Figure 12-3. Additionally over 40% of respondents selected more than one Frontier as the Frontier they work in, indicating much of the research in HEPA extends beyond a single primary area.

The survey team made a deliberate effort to not ask for opinions on specific experiments. Because the field of high energy physics moves quickly, the choices given in previous surveys were not particularly relevant today. Additionally, there was concern that this type of question would simply reflect the relative number of participants from different experiments involved in Snowmass.

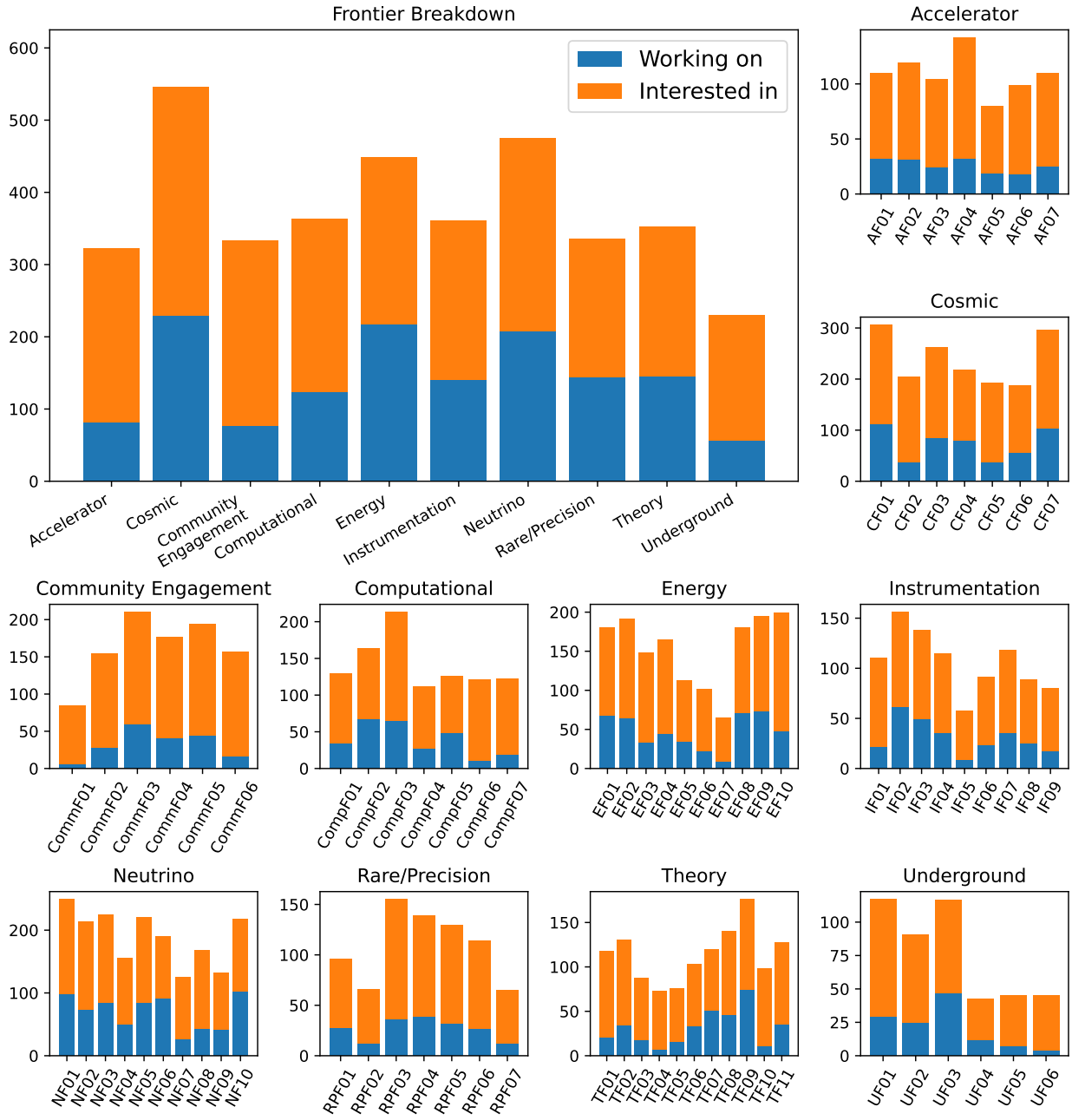

Figure 12-3. *The survey team asked respondents to indicate which Frontiers and Topical Groups they were working in or had an interest in, even if they were not directly working on such physics.*

Instead, respondents were asked more general questions about where they felt the field *was moving* and in which direction they felt the field *should be moving* Figure 12-4. A plurality of respondents indicated they felt the field "should be going" for a balanced approach between small and large collaboration sizes, focused and broad experimental programs and facilities, new and continuing directions and programs, and new and established topics. Overwhelmingly, the biggest imbalance between where respondents felt the field

was going compared to where it should be going was in the difficulty in hierarchy ascension. Nearly 70% of respondents said the field was heading towards a 4 or 5 (with higher numbers implying more difficulty), while there was an overwhelming preference (with $> 70\%$) among respondents for this to become easier.

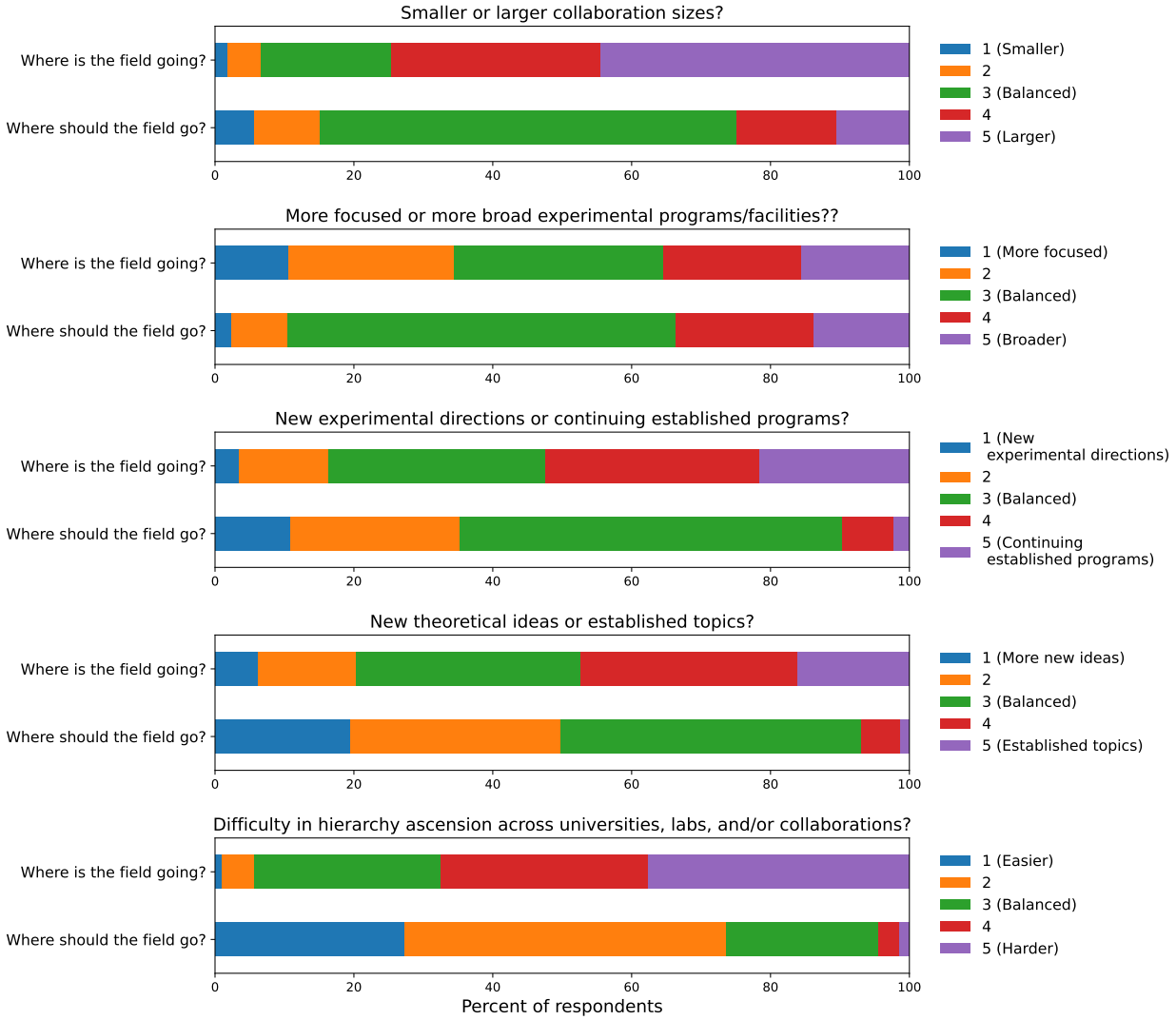

Figure 12-4. *For a range of topics, respondents were asked to rate (on a 1-5 scale) in which direction they thought the field was currently going and where they thought the field should go.*

Large-scale experimental projects in HEPA often span decades and even funding agencies, which can cause unique challenges to the careers of scientists in the field. When asked if they believed long timescales of experimental programs in HEPA were concerning for the field, a plurality of respondents answered "Yes", with another $\sim$ 30% of respondents indicating "Maybe". Only about 20% of respondents answered a definitive "No" Figure 12-5.

The survey also asked respondents to select what types of data, software or analysis codes they believed should be made open source alongside published results. Most respondents were in favor of publishing data/results as they appear in publications, but a significant majority of respondents also said they supported

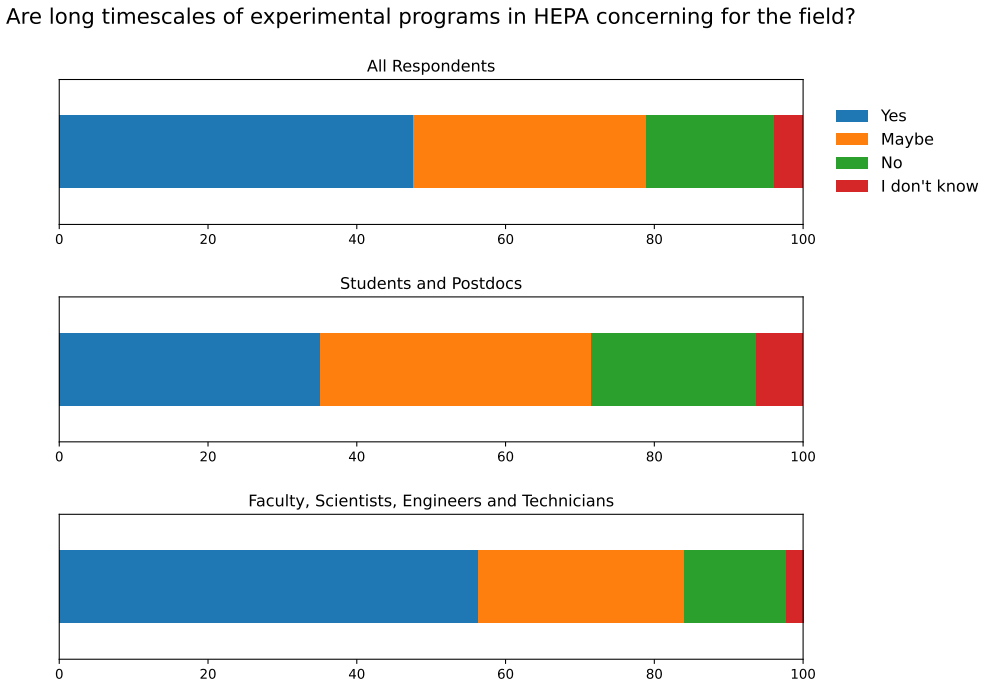

Figure 12-5. *Respondents were asked whether they believed long timescales of experimental programs in HEPA were a concern for the field.*

"Minimally processed (ready for analysis) data", "Publication-specific analysis code and simulations", and "Fully corrected and reconstructed data / legacy samples" being made open source Figure 12-6.

When asked about which aspects of research in HEPA they believed were underfunded, the most frequently selected option was "development and maintenance of open source software", which over half of respondents selected. Over 40% of respondents also selected "public data releases and associated storage", "Opportunities for early-career researchers to attend workshops, schools, conferences and meetings", "Membership opportunities in collaborations for scientists with limited funding", and "undergraduate research experiences" Figure 12-7.

There has also been a growing awareness within the HEPA community about the climate emergency in society [10]. When asked to what extent they know about the HEPA community's environmental impact, on average, respondents said they do not know much about it. Early career scientists report knowing slightly less than senior researchers. The survey team also asked how concerned the respondents were about the HEPA's environmental impact. The responses are, on average, more neutral. Nevertheless, early career members seem to be more concerned than senior researchers. Finally, the respondents think, on average, that it is important to take into account the environmental impact when making decisions on future HEPA projects. This particularly emerges from early career researchers, who will most likely cope with more severe effects of the climate emergency.

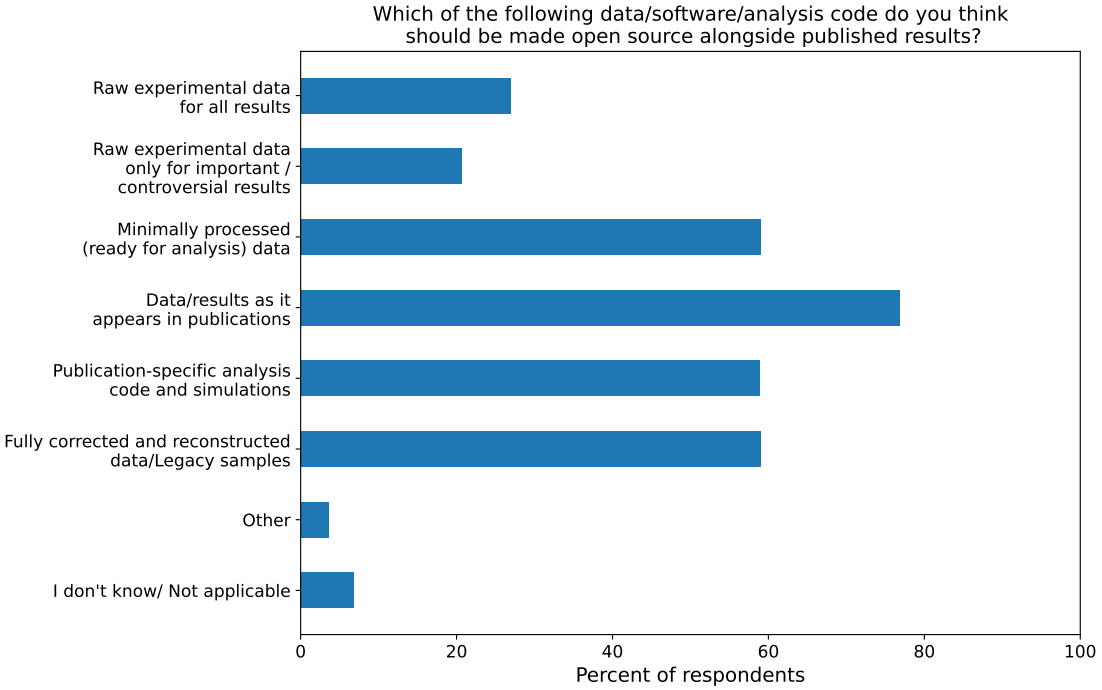

Figure 12-6. *Respondents were asked which data/software/analysis code they believed should be made open source alongside published results.*

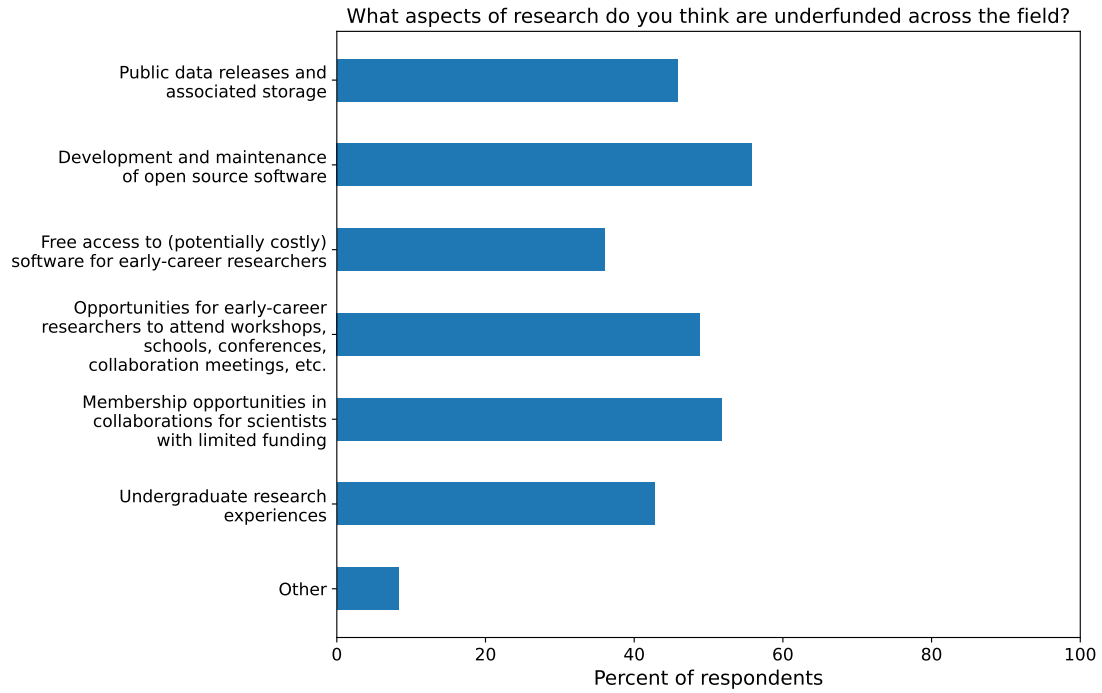

Figure 12-7. *Respondents were asked what aspects of research in HEPA they believed were underfunded.*

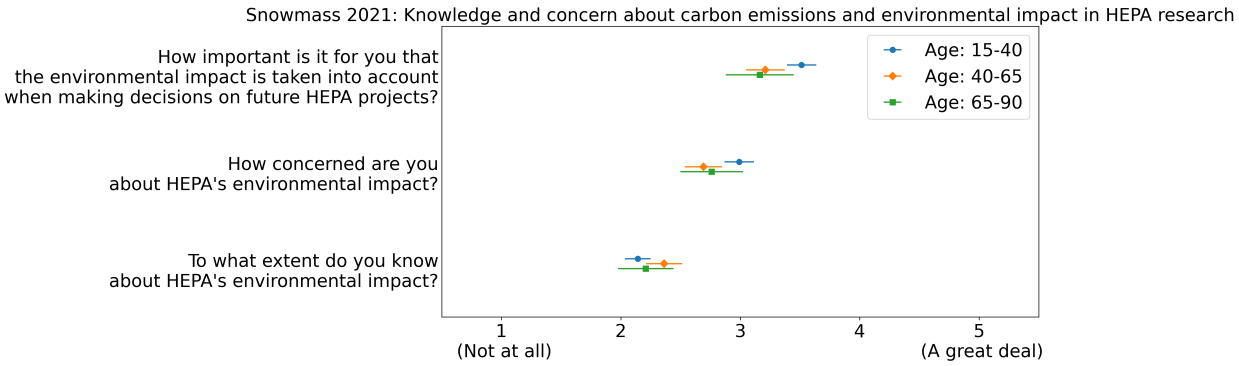

Figure 12-8. *Perception of the community on the HEPA community's environmental impact.*

12.2.2 Survey Recommendations

The remainder of the survey focused on demographics, careers, workplace culture, diversity and racism, caregiving responsibilities, and the impacts of COVID-19. Here we discuss several recommendations based on the data presented in the Snowmass 2021 Community Survey Report. The survey team gathered, analyzed, and synthesized the data. Their synthesis included a discussion of the data that included some of the key findings on the current state of the field and potential areas for improvement. The recommendations in this section are derived from the survey team's discussion, and several members of the SEC survey team have helped develop this section.

In examining human experiences in the 2021 survey, the survey team found so much honesty and openness within the Snowmass community. People were honest about how much the COVID-19 pandemic has affected their career and personal life; they were honest about the experiences they faced involving harassment and racism; and they were honest about where they think the field is heading over the next decade. The survey uncovered unique perspectives and experiences for different career stages, primary workplaces, caregiving responsibilities, and across gender and racial lines. Yet the survey also revealed many similarities among the members of the Snowmass community, including concerns about salary, HEPA's environmental impact, and directions in which they would like the field to progress. Finally, many 2021 survey respondents reported feeling a lack of support in various places – between peers and work colleagues, from an advisor, at the institutional level, or by the field as a whole. We each face a unique set of challenges for however long we work in HEPA, and on an individual level, we can extend more sympathy and understanding to our immediate working group, students, and other collaborators. However, individual cultural changes are not enough – systemic changes need to be made by institutions and funding agencies to provide effective support for everyone, especially for early career scientists and those with caregiving responsibilities. By exploring the varied experiences of scientists in and out of HEPA, the 2021 survey exposed many concerns and disparities that should be addressed through meaningful action and cultural changes. At the time of the next Snowmass process, the next survey can be used to check for improvements in these areas.

SEC Survey Recommendation 1: Institutions, funding agencies, and scientists should make systemic changes to provide early career scientists with adequate compensation.

A large number of PhD students (45.4%) and Postdocs (39.6%) report feeling their salary probably or definitely is inadequate (Figure 12-9), indicating there might be a systemic issue with adequately compensating early career scientists for their contributions to HEPA. It is common for PhD students to be paid less for their contributions (e.g., due to the "trainee" or student aspect of the position), and there is little to no compromise for stipend amounts. Lack of compromise is also the case for Postdocs at some institutions, especially for institutions with high-demand positions or with strict salary requirements. Some Postdocs can negotiate their salaries, but those skills are not within the scope of the average U.S. graduate school curriculum.

Salary amounts should (at minimum) cover the cost of living for the specific institution's location, and they should increase every year to cover the cost of inflation. For universities, increasing stipends for graduate students might be handled outside of the physics department, so faculty and scientists can be advocates and consistently place pressure on the administrators who have control over determining graduate school stipends and Postdoc salaries. Funding agencies should also take cost of living and inflation into account while awarding fellowships to early career scientists and grants to faculty and scientists, so that research groups have adequate funds to compensate their students and Postdocs. Furthermore, graduate programs should offer training (e.g., in a class, seminar, or through a broader institutional effort) on how to negotiate salaries, and they should advertise or require the training at some point during the graduate curriculum.

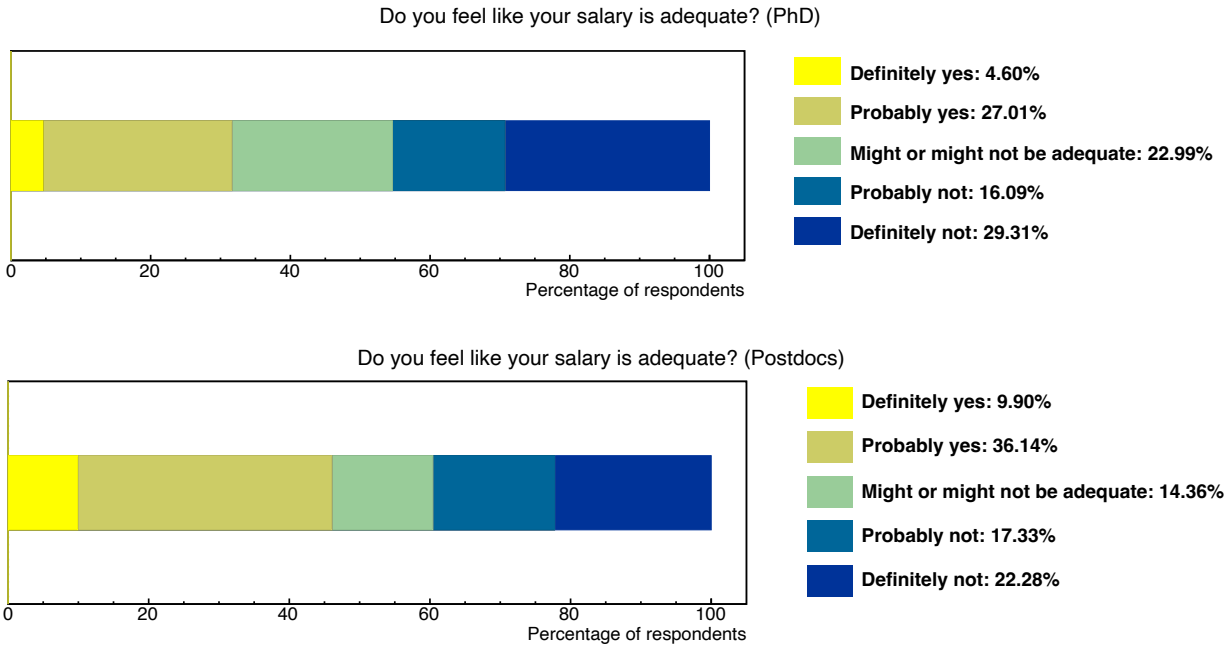

Figure 12-9. *The survey team asked PhD students and Postdocs how they felt about their salary. The majority of PhD students (97.8%) and Postdocs (99%) answered this question.*

SEC Survey Recommendation 2: Institutions and funding agencies should collect data on pay differences between junior and senior faculty and scientists and develop pay policies to address junior faculty and scientists' compensation concerns.

When asked about their salaries, more tenure-track faculty think their salary probably or definitely is inadequate compared to tenured faculty, indicating a need to revisit and revise policies on faculty compensation. Similarly, when the survey team compared responses about salaries, scientists ranked the lowest (below senior scientists, tenure-track faculty, and tenured faculty) in terms of salary adequacy, and they also ranked higher than senior scientists in terms of salary inadequacy. The results continue to indicate that scientists in more junior positions are less satisfied with their salary, and the same sentiment is not shared with scientists in more senior positions. Conversely, more senior scientists reported that their salary is adequate at some level compared to the other three groups, and far fewer scientists and senior scientists reported that their salary is inadequate on some level compared to faculty. This difference could stem from the difference in pay between national labs and universities, and it indicates that national labs might be offering a more reasonable salary compared to universities.

SEC Survey Recommendation 3: Institutions should track career outcomes and adequately train early career scientists to move into a variety of job sectors, especially industry positions.

The 2021 survey results indicated less of a desire to remain in academic HEPA than to seek employment in another sector, both from the early career scientists currently in HEPA and the non-academics who recently departed HEPA for industry jobs. A majority of faculty and scientists also reported that they have thought about leaving HEPA or their institution. Even if scientists strive to remain in HEPA, they

are predominantly concerned about job availability and already feel the competition surrounding them in their current workplace. Institutions should provide early career scientists opportunities and training for professional development skills (e.g., negotiating salaries), so that they can effectively prepare for a variety of job sectors beyond HEPA. Funding agencies can also create opportunities for early career scientists to collaborate with industry partners, offering a bridge between HEPA and industry while also exposing early career scientists to a larger diversity of job sectors and mentors.

The survey shows that early career scientists with recent job offers are largely staying in HEPA. Overall, the vast majority of early career scientists who accepted or plan to accept a position applied for (and accepted) Postdoc positions. Even if PhD students ultimately accepted a non-academic position, they likely also applied for academic positions. While PhD students collectively applied for academic positions, Postdocs were more varied in their job search, where about two-thirds reported applying for academic and non-academic jobs alike. Compared to graduate students, more Postdocs indicated they were switching to a different job sector.

Early career scientists who are applying for jobs are largely interested in remaining in HEPA. Overall, early career scientists expressed much more interest in applying for academic positions versus industry positions. The results indicate that universities might not adequately advertise or train their students on how to apply for industry jobs, as the survey team found that early career scientists located outside of universities were more likely to apply for STEM industry positions. When asked to comment on why they chose their top sector, many early career scientists who rated academic positions highly wrote about their love for teaching and research. There was also a group of early career scientists who wrote about their struggles to remain in HEPA (e.g., not enough permanent positions, the expectation to complete multiple postdocs, etc.), and others who expressed dissatisfaction with HEPA and a desire to switch to a different sector. The early career scientists who took the 2021 survey are aware about the lack of permanent positions and highly competitive nature of HEPA. While the majority continue to apply for academic positions, some early career scientists are disappointed, dissatisfied, and moving out of HEPA. Furthermore, early career scientists who are applying for jobs are deeply concerned about job availability regardless of the sector. On the whole, early career scientists indicated much more concern about academic job availability compared to the industry job sector.

Overall, early career scientists are applying for non-academic jobs (even if they ultimately remain in HEPA); there exists a subset of scientists who are dissatisfied with HEPA and wish to switch job sectors; and early career scientists expressed a deep concern for academic job availability. Outside survey data found that early career scientists (specifically Postdocs) are passionate about their research, but they also acknowledge the challenges of low pay, work-life balance, and a competitive job market [11]; similar results have also been observed in other surveys conducted during the pandemic [12].

The 2021 survey also received a balanced mix of respondents with a variety of age ranges, with a group who recently left HEPA and another group who left decades ago. This allowed us to compare their responses to look for changes in HEPA's job market and culture. The results indicated that younger and recently departed non-academic respondents seem less interested in an academic future: Significantly more non-academic respondents over 40 years old reported that they attempted to find a job in HEPA, and fewer respondents who left HEPA recently reported looking for an academic job. These results are concerning for early career scientists in HEPA who are planning to apply or currently applying for jobs, especially with the reports from early career scientists in HEPA about their dissatisfaction with HEPA and desires to switch sectors. Surveys conducted outside of the Snowmass process show that Postdocs are concerned about their career prospects and lack of support from their supervisor during the pandemic [13], and these sentiments could, at worst, lead to a generational abandonment of HEPA as a whole.

Institutions should train their early career scientists to explore a variety of job sectors comfortably and confidently. According to a report from the Organisation for Economic Co-operation and Development (OECD), institutions should track career outcomes from their PhD students so that the U.S. part of HEPA can better understand job opportunities on a local level along with what challenges new PhD holders face while transitioning into the next stage of their career. Institutions should also provide opportunities (e.g. seminars or internships) to Postdocs so they can gain professional development skills [14]. According to the survey results, networking is critical for those who are planning to leave HEPA, so both institutions and funding agencies should create networking opportunities.

SEC Survey Recommendation 4: Institutions, national labs, and senior members of HEPA should support their employee's struggles with U.S. visas and immigration policies by advocating for updated policies, a streamlined application process, and inclusive hiring processes.

The survey revealed that Postdocs are affected more by visa restrictions compared to graduate students, and some Postdocs applying for jobs reported that immigration issues were an important concern for them. Our results indicate that immigration issues disproportionately affect early career scientists in other racial groups, while White early career scientists remain largely unaffected. Current U.S. visa policies are largely inadequate to support Postdocs' transitions into non-academic job sectors [15]. Immigration concerns should always be taken into account while training Postdocs how to navigate various job markets.

The survey also shows that more tenured faculty take place in hiring compared to tenure-track faculty, where around half report that past or present U.S. policies on visas had some negative effect on their hiring ability. Additionally, scientists on the whole reported that past or present U.S. policies on visas had some negative effect on their hiring ability, indicating that past and present U.S. policies on visas have affected hiring at both universities and national labs in similar ways.

SEC Survey Recommendation 5: Principal investigators and institutions should offer comprehensive support to their early career scientists.

PhD students and postdocs rely on the support of their advisors or supervisors, not just their work colleagues. Principal investigators should offer support to their early career scientists, whether that be advocating for institutions to offer comprehensive mental-health services; exhibiting flexibility and patience toward their students and Postdocs; or advocating for increased salaries or benefits for their students and Postdocs. Additionally, institutions should provide resources and policies to support a healthy workplace culture and mental health, including providing insurances that fully cover off-campus therapy.

SEC Survey Recommendation 6: Institutions and funding agencies should further investigate changing cultural trends in HEPA, including changing job expectations and increasing competition in the job market, and adjust policy accordingly.

The average tenure-track faculty who took our survey noted more time as a Postdoc and more time looking for faculty positions compared to their averaged tenured faculty counterpart. This indicates that scientists searching for permanent positions in HEPA may spend longer amounts of time as an early career scientist. Furthermore, tenure-track faculty respondents set themselves apart from their tenured colleagues by forming two distinct groups: Those who spent 3-4 years as Postdocs, and others who spent 6-7 years as Postdocs. This seems to indicate that some tenure-track faculty completed two or more postdocs before securing their faculty position. Tenured faculty respondents roughly reported 3-5 years as a Postdoc. These results hint

at changes within HEPA; expectations for faculty have changed over the past three decades in places such as collaborations and departments and the job market is more competitive now compared to the recent past. Scientists and senior scientists reported spending similar amounts of time as Postdocs, and although the difference is not significant, scientists did report spending a couple more months looking for a job compared to senior scientists. Similar to tenure-track faculty, the results from scientists might indicate the high competition currently being experienced in the HEPA job market.

Another hint to HEPA's changing culture is that the majority of teaching, tenure-track, and tenured faculty would prefer a reduced teaching load on some level, while the limited number of retired faculty respondents reported that they would not have preferred a reduced teaching load. Perhaps teaching expectations have changed over the past three decades, or perhaps other responsibilities have taken priority over teaching.

Additionally, compared to faculty respondents, tenure-track faculty reported far fewer of their PhD students and Postdocs as employed after graduation. More tenure-track faculty also reported 0% of their PhD students and Postdocs as employed. This could be related to early career scientists' concern over job availability, especially if both groups of scientists are applying for academic positions. Furthermore, the survey team discovered a similar report between scientists versus senior scientists for the PhD students and Postdocs they mentor. Because there is a difference between the responses of tenure-track and tenured faculty members, this once again indicates that HEPA's culture and job market have evolved over the past three decades. Figure 12-10 further highlights the concern about the availability of positions at universities and national labs, especially when compared with industry positions (Figure 12-11).

While further investigation into these trends is needed to better quantify their sources and effects, it is clear that institutional and funding agency policies will need to change with the culture. For example, more long-term intermediate positions may be necessary given the extended timelines for career advancement, and assessment criteria may need updating to reflect changing expectations.

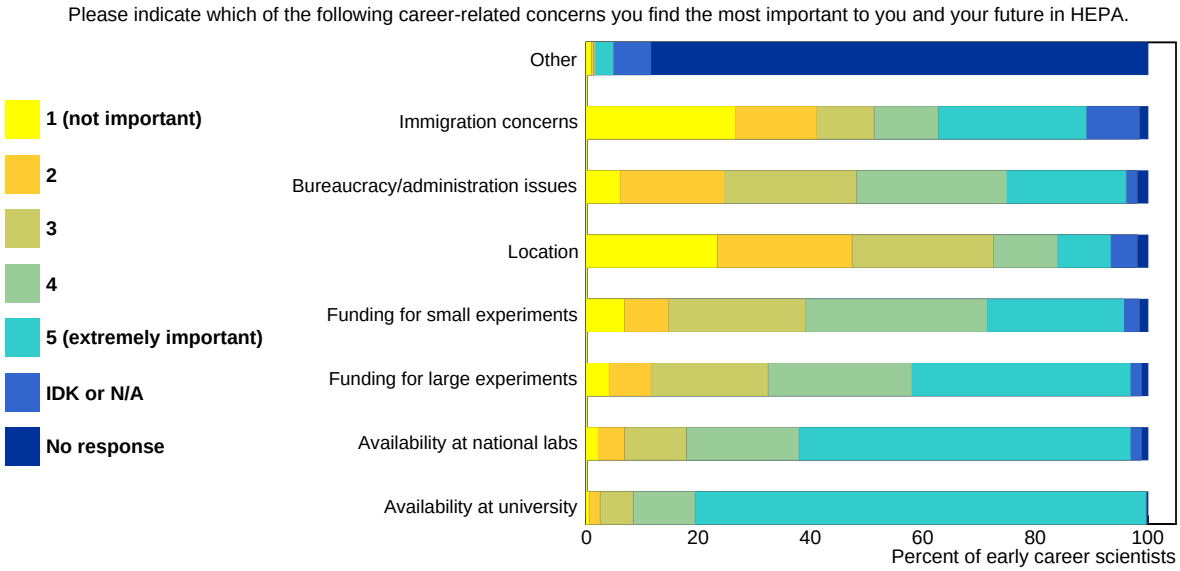

Figure 12-10. *The survey team asked early career scientists who were likely to apply to academic positions about their career-related concerns.*

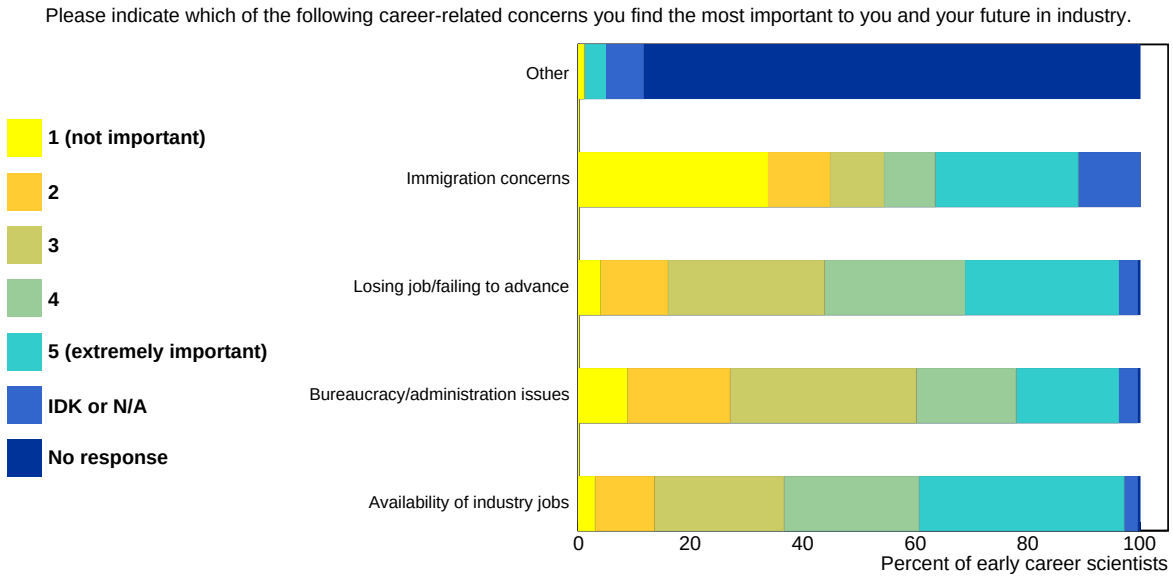

Figure 12-11. *The survey team asked early career scientists who were likely to apply to industry positions about their career-related concerns. A little over half of the early career scientists surveyed saw this question.*

SEC Survey Recommendation 7: Undergraduate students should be compensated for their research responsibilities.

One concerning result from the survey was that about one-tenth of tenure-track faculty and one-fifth of tenured faculty reported not compensating their undergraduate students for their research responsibilities. This result is coupled with reports from some undergraduate student respondents that they are not compensated for their research responsibilities. Similar to unpaid internships, uncompensated research is an opportunity that is disproportionately unavailable to students from lower income backgrounds or those who lack financial support for their education expenses because they are unable to spend their time on uncompensated labor [16].

As one method to increase inclusiveness within HEPA, undergraduate students should be compensated for their research responsibilities, whether it is through financial compensation, course credit, outside fellowships, work study programs, or other means. This may need to be handled on a department-by-department basis, but funding agencies should also allocate adequate funding toward compensating undergraduate students in faculty research groups. Funding agencies should also continue to fund fellowships and programs (e.g., the NSF REU program [17]) that support and nourish undergraduate student research opportunities.

SEC Survey Recommendation 8: Institutions and funding agencies should provide support for outreach, mentoring, and advocacy efforts while continuing support for research, especially for underrepresented groups in physics. Institutions should include service work like mentorship, outreach, and advocacy in job expectations, ensure that faculty and scientists are given adequate time and credit for this work, and ensure that service work is equitably distributed.

The survey results indicate that institutions are not systemically hindering research, outreach, or mentoring for their faculty members. On the other hand, faculty reported that their institutions help with research much

more than outreach or mentoring. Furthermore, more faculty reported that their institution neither helps nor hinders mentoring and outreach compared to research. These results indicate that institutions are not actively helping with faculty outreach or mentoring efforts. Female faculty might also be disproportionately affected by their institutions compared to male faculty, as our results showed more female faculty reporting that their institution hinders their research on some level.

The vast majority of faculty work more than the standard 40-hour work week: A little less than half of the faculty respondents reported committing around 23 hours per week to research at the very least, and a quarter of faculty reported committing at least 23 hours a week to teaching. Overall, the average faculty respondent commits the most amount of time to research, fairly equal amounts of time committed to teaching and mentoring, and far less time to outreach and advocacy – a hierarchy that seems reasonable but might be unbalanced in terms of actual time committed. When the survey team compared White faculty with faculty in other racial groups, they found that the latter group reported committing more time to research, outreach, and advocacy. Over a quarter of all faculty reported committing time to other career items – mostly service and administrative work – and female faculty reported spending more time on these responsibilities compared to male faculty. The faculty members commit similar amounts of time to their administrative duties and their teaching/mentoring, leading to an unbalanced set of commitments.

When it comes to comparing time commitments, nearly two-fifths of scientists reported spending almost all of their time on at least one career item, one-fifth more than faculty who made the same report. With forty-three percent of scientists committing at least 22 hours per week to leadership and ninety percent of scientists reporting some leadership responsibilities, the results indicate that national labs provide ample opportunity for leadership opportunities. The survey team also found that scientists older than 50 years old commit less time to leadership compared to those younger than 50, a sensible and reasonable result. More scientists reported committing more time to leadership than research, but this isn't too concerning if these leadership responsibilities bear research-rich fruit. The survey team found differences between the amount of time scientists commit to career-related items across gender and racial lines – particularly when it came to research, service, and leadership. Female scientists disproportionately reported spending more time on service work compared to male scientists; White scientists reported committing more time to leadership; and scientists in other racial groups reported committing more time to research.

With the other half of their 40-hour work week committed to research, perhaps it's not too surprising that scientists commit far less time to items outside of research and leadership. For example, scientists reported spending less time on mentoring compared to faculty reports, a result that is unsurprising, although dedicated funding for national lab-based student research opportunities could also help increase the mentoring opportunities for scientists. Scientists commit much less time to advocacy than all other career items over the course of a year. Scientists are employed as government contractors, so this may in part be due to less legal flexibility due to the Hatch Act of 1939.

Another hint of institutional differences arose when the survey asked about whether institutions help or hinder outreach and mentoring. Compared to faculty, more scientists reported that their institution hinders outreach and mentoring on some level. Nearly a quarter more female scientists reported that their institution hinders advocacy compared to reports from male scientists, and more male scientists indicated that they didn't know whether their institution helps or hinders advocacy efforts. This indicates that advocacy efforts might not be prioritized by national labs and might even be hindered in some cases, and this hindrance is disproportionately noticed by female scientists.

SEC Survey Recommendation 9: Funding agencies should move toward funding models that support increased collaboration like block grants to universities.

Compared to other career stages, faculty reported the highest amount of competitiveness at their workplaces and the lowest satisfaction level with the support from their colleagues. While the majority of faculty reported feeling like their salary probably or definitely is adequate, about one-fifth of faculty feel the opposite. A significant portion of the faculty who responded to the 2021 survey face enormous time commitments and responsibilities at work and home while lacking support from their colleagues and the field overall. Funding agencies don't have to play a passive role in light of these results; for example, they could shift funds into block grants in which universities directly pay salaries to their faculty members [18]. This could reduce some of the competition faced by faculty who compete for grants, and it also reduces the workload and headache for faculty with administrative or grant/funding time commitments.

SEC Survey Recommendation 10: Institutions should improve how they support scientists with caregiving responsibilities, especially those most impacted by the effects of the COVID-19 pandemic. This includes encouraging reasonable work hours, providing adequate salaries, offering paid Medical and Family leave to all employees and supporting employees who use it, subsidizing or offering childcare to their employees, and fairly evaluating caregivers' drop in productivity in the context of current events in hiring and promotion committees.

A significant portion of the survey respondents (including early career scientists) had some form of caregiving responsibilities (28.3%). The majority of caregivers reported caring for children, although some respondents reported caring for seniors, a person with a disability or medical condition, or some combination of those three groups. Disproportionately more female caregivers reported they are sole or primary caregivers compared to male caregivers, while more male caregivers described their responsibilities as part-time caregiving. Female caregivers reported slightly less free hours per week on average and more female caregivers also indicated substantial career effects because of their caregiving responsibilities, including rearrangement of their work schedule, decrease of hours, or unpaid leave. These results seem to hint that female caregivers are not as widely supported within HEPA, and some of them face extra struggles like sole caregiving.

When asked about the level of support they receive in academia as a caregiver, the scientists who participated in this survey feel the most support from their peers or immediate working group, and they feel the least amount of support from funding agencies and the overall field. When broken down by primary workplace, results indicate that caregivers at universities and other institutions where caregivers deal more directly with funding agencies face an extra set of pressure and competition with no additional support to match.

While comparing caregivers' reports about their support from peers versus their place of employment, the survey team found that the responses formed two main groups: caregivers who reported feeling the same levels of support between their peers and their place of employment, and caregivers who reported less support from their place of employment. Recall that faculty also reported the lowest satisfaction level with the support from their colleagues when compared to other career stages – a troubling result when it seems like some caregivers might need to rely on their peers at times when their place of employment does not provide adequate support. Additionally, the first group of caregivers contains those who reported feeling no support from either their peers or their place of employment, highlighting that institutions can continue to improve how they support scientists with caregiving responsibilities.

The HEPA field overall is providing inadequate support to many of its caregivers, and according to the 2021 survey results, the lack of support disproportionately affects caregivers across different gender, racial, and age lines. Disproportionately more female caregivers reported feeling little to no support from their place of employment, funding agencies, and the field. More caregivers in other racial groups and more caregivers younger than 50 years old also reported feeling lack of support from funding agencies and the field. Keep

in mind that the majority of all caregivers reported little to no support by the field; when broken down by gender, the same proportion of male and female caregivers respectively reported feeling some support as a caregiver by HEPA, and more male caregivers reported that they don't know whether they feel supported by the field. Clearly the field can extend more support to all its scientists with caregiving responsibilities.

Caregivers in HEPA were profoundly impacted by the COVID-19 pandemic, and they continued to feel these impacts at the time they took the survey. The majority of all caregivers with children reported less overall productivity compared to pre-COVID levels; they also reported significantly more time and effort spent on caregiving responsibilities during the pandemic. More female caregivers, caregivers in other racial groups, and caregivers younger than 50 years old reported spending more time and effort on caregiving compared to pre-COVID time and effort. For caregivers of seniors or people with a disability or medical condition, half of these caregivers reported less overall productivity compared to pre-COVID levels, and over half reported more time and effort spent on caregiving during the COVID-19 pandemic. Caregivers also expressed similar sentiments when asked to comment about their experiences; they also expressed an inability to return to pre-COVID productivity levels despite their best attempts. Finally, caregivers did not widely report additional resources for childcare provided by their institutions during the COVID-19 pandemic.

When comparing caregivers with children in different age groups, the results revealed that more caregivers with younger children reported severe effects due to the COVID-19 pandemic, and caregivers with younger children (notably, young children in school) reported more time and effort spent on caregiving during the COVID-19 pandemic. The results revealed that more caregivers with older children reported the same overall productivity compared to pre-COVID levels; at the same time, more caregivers with children 14 years old or older – or younger than 6 – reported the same amount of time and effort spent on caregiving. Overall, more caregivers with children younger than 14 years old reported spending more time and effort on caregiving compared to pre-COVID time and effort. More female caregivers reported having preschool-aged children compared to male caregivers, while more male caregivers reported having children older than 5 years old. All of these results indicate that female caregivers in HEPA are disproportionately affected by the COVID-19 pandemic, impacting overall productivity levels and requiring more time and effort spent on their caregiving responsibilities.

Several interesting differences arose when the survey team split caregivers' responses by different primary workplaces, notably universities and national labs. More caregivers at universities disproportionately indicated substantial career effects because of their caregiving responsibilities. When broken down by career stage, faculty caregivers reported more or substantial effects due to their caregiving responsibilities compared to scientist caregivers. These results indicate that universities might not be providing adequate support for scientists with caregiving responsibilities.

Faculty and scientists (which made up a large portion of the respondents with caregiving responsibilities) reported working long hours, with significant time commitments toward a variety of career-related items. The average caregiver reported being free of all caregiving responsibilities for about 34 hours per week (far fewer hours than what the majority of faculty and scientists spend working per week), and caregivers at national labs reported several more free hours compared to caregivers at other institutions. Around a quarter of faculty and one-fifth of scientists reported that their salaries are probably or definitely inadequate – so there's room for institutions to encourage reasonable work hours and increase salary, two effective methods of supporting those with caregiving responsibilities [19].

The average respondent with caregiving responsibilities has access to some form of Family and Medical leaves from their employer, and they are not not suffering any professional setbacks in the event they utilized Family and Medical leave. While the caregiver might have access to Family and Medical leaves, the leaves might be unpaid; some caregivers also reported that their institution does not offer Family and

Medical leaves. More caregivers at universities and white caregivers reported that they don't know if their place of employment offers Family and Medical leaves. Disproportionately more male caregivers reported that they didn't know when it came to a few caregiving topics: More male caregivers didn't know if their place of employment offers Family and Medical leaves, whether their employer offered leaves during a time when they could have taken leaves, or whether they suffered any professional setbacks due to their taking of leaves. Caregivers also reported some professional setbacks while utilizing Family and Medical leaves, and this was disproportionately reported by female caregivers, caregivers in other racial groups, and caregivers at national labs. Institutions can offer paid Family and Medical leaves as one means of supporting the scientists with caregiving responsibilities [19], and institutions can actively encourage and support the scientists who need to utilize the leave.

With the COVID-19 pandemic predominantly affecting access to childcare and productivity levels, caregivers in HEPA require more support than ever from all angles: Work colleagues, department or institution administrators, and funding agencies. While specific action can be taken by the U.S. government concerning caregivers in all U.S. job sectors [19], institutions do not need to wait to implement such changes. Institutions should offer adequate salaries and paid Family and Medical leaves for all employees. Institutions can also support caregivers by subsidizing or offering childcare to their employees. Hiring and promotion committees should fairly evaluate caregivers' drop in productivity in the context of current events. Scientists with caregiving responsibilities make valuable contributions and bring an irreplaceable perspective to HEPA; they should not be left behind by the field.

The responses and comments from caregivers were deeply honest, personal, and sometimes heartbreaking. We should not ignore or dismiss the real and valid responsibilities that scientists in HEPA face alongside their research commitments.

SEC Survey Recommendation 11: Institutions and funding agencies should evaluate and assess the impacts of the COVID-19 pandemic over the coming years and adapt policy to support those most affected.

The COVID-19 pandemic had an inseparable effect on all of the results of the 2021 survey. In addition to the direct effects on the Snowmass process (both in the timeline and the nature of the work), the pandemic fundamentally altered the every day lives and work of all the members of the HEPA field. Our results found that these effects—some temporary, others permanent and career-altering—had varying impacts across different groups and career stages, while the levels of support offered by institutions were similarly varied. Caregivers in particular were heavily impacted, and it may be a few years before the true extent of the impacts of the COVID-19 pandemic can be properly assessed.

SEC Survey Recommendation 12: Institutions should adapt workplace policy to be more flexible with work from home in the future.

The COVID-19 pandemic changed working arrangements, and the survey inquired about current and preferred teleworking arrangements. This survey was conducted over several weeks and asked respondents to tell us their current teleworking arrangement. The survey team found that 69.2% of respondents spent a majority of their time working from home. Going forward, a large group, 44.5% prefer to work $1-2$ days from home, while 26.7% prefer their workplace, and 9.25% would prefer to work only from home. This could indicate a shift in how the workplace is utilized for members of the field in the future.

12.3 SEC at the Community Summer Study

The Snowmass Community Summer Study (CSS) took place from July 16 to 26, 2022. It was held in hybrid format and hosted by the University of Washington, with in-person activities held on the Seattle campus. The CSS planning committee included two early career members who served as representatives of SEC and the community at large.

SEC organized a number of sessions at the CSS, with a workshop-wide plenary that contained talks on the SEC core initiatives, survey report, and long-term EC organizations across HEPA. Early career physicists took the lead in many other areas, including several successful events focused on industry careers, networking, and perspectives. They also hosted community discussions on mental health and invisible disabilities and were represented in panel discussions on community topics such as COVID-19 and career development. The level of interest in the early career perspective for Snowmass and the future of SEC led to the scheduling of an additional feedback session on early career issues in the final days of the meeting. Various informal social gatherings also took place to connect early career scientists beyond professional capacities.

Early career CSS participants were vocal and enthusiastic about the discussion of physics drivers and future experimental facilities. They were contributors to white papers across all frontiers, and gave talks in sessions. T-shirts advocating for a muon collider and pins for the Cool Copper Collider were introduced by early career scientists and seen on participants throughout the CSS.

A form was issued to the early career community following the CSS, to provide a last opportunity to share feedback and impressions. The form requested the user's academic/career level and gave the option to select one of five areas of feedback: on the Community Summer Study content or discussion, on content or discussion that overlaps with a frontier report, on recommendations emerging from SEC survey data, on personal input or input from other colleagues, or perspectives on future physics drivers and facilities. A field was also provided to indicate the target audience of the feedback, namely the field (all members), the field (senior members), funding agencies, early career organizations, or other.

A total of 33 form responses were recorded. These primarily came from postdocs and on the topic of future physics perspectives, which called out support for next-generation cosmology experiments. Considerable discussion took place within the EC community on the role of voiced support for specific physics facilities, and the amount of care that should be used to disseminate these opinions. A numerical poll was not distributed to avoid the biasing of large experiments or frontiers over smaller ones.

12.4 Recommendations

The recommendations in this section were prepared by the HEPA EC community and are a supplement to the survey recommendations in Sec. 12.2.2. They include recommendations from contributed white papers and community feedback obtained throughout the Snowmass process.

12.4.1 Increasing Early Career Representation in Decision-Making Bodies

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SEC Recommendation 1.1 - Early career representatives should be included in HEPA community-wide decision-making bodies and advisory panels such as HEPAP and P5.

SEC Recommendation 1.2 - Funding agencies should increase opportunities for early career participation in review panels.

SEC Recommendation 1.3 - HEPA experiments should pursue organizational change to include early career representatives in all decision-making bodies.

SEC Recommendation 1.4 - The APS DPF Executive Committee should extend the term of the early career representative to match that of members at large and should increase the number of early career representatives in that body to two.

SEC Recommendation 1.5 - The users community organizations such as USLUA, SLUO and the Fermilab Users Executive Committee should explicitly codify the inclusion of early career representatives.

SEC Recommendation 1.6 - HEPA Experiments should foster the existence of early career organizations and provide them with resources to pursue new initiatives.

SEC Recommendation 1.7 - DOE National Labs should continue to support early career groups and their participation in community-building activities where they exist and encourage their creation at labs where they do not yet exist.

12.4.2 Addressing Accessibility and Economic Equity

SEC Recommendation 2.1 - Funding agencies, universities, and DOE National Labs should work together to sustainably increase the pay grade of graduate students, postdoctoral fellows and others in equivalent career stages according to their skills in order to reach competitiveness with industry salaries and improve their quality of life.

SEC Recommendation 2.2 - APS and/or DPF should increase the funds available for travel assistance to early career representatives on decision-making bodies to ensure equal access.

SEC Recommendation 2.3 - Funding agencies should consider language that encourages participation of students and postdocs in decision-making bodies and other service to the field as part of the mentorship and retention component of their grant proposal evaluations.

SEC Recommendation 2.4 - Funding agencies should further explore funding opportunities that may be available exclusively to early career individuals as principal investigators.

12.4.3 Robust Equity, Diversity, and Inclusion

Early career scientists are disproportionately affected by issues of discrimination and harassment. Additionally, the power dynamics of between senior members in the field and early career scientists are particularly strong, which can exacerbate these concerns. The following recommendations are in line with those in the Community Engagement Frontier report, but have been drafted to address issues that disproportionately affect early career individuals.

SEC Recommendation 3.1 - Funding agencies should significantly increase the ability to investigate and address instances of harassment and discrimination directly as well as implement real consequences for grantees when necessary and without relying on reports from institutions.

SEC Recommendation 3.2 - The field must significantly increase programs of in-reach, training, and awareness of the Americans with Disabilities Act (ADA) and its consequences for workplaces and professional environments.

SEC Recommendation 3.3 - Universities and national laboratories must implement and impart specific training to educate early career scientists on the step-by-step process of addressing and reporting instances of harassment and discrimination, as well as their potential consequences.

SEC Recommendation 3.4 - Large experimental collaborations and projects in both experimental and theoretical physics must continue to develop policies to investigate and address instances of harassment and discrimination directly as well as implement real consequences for collaborators when necessary.

12.4.4 Empowering SEC for the next Snowmass Process

SEC Recommendation 4.1 -APS should provide additional dedicated funding to DPF during Snowmass years in order to support accessibility and increased participation of SEC.

SEC Recommendation 4.2 - DPF should formalize connectivity with early career leadership throughout APS, such as in other divisions that participate in Snowmass like the Division of Astrophysics (DAP), or in the Fora on Graduate Student Affairs (FGSA) or Early Career Scientists (FECS).

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13

Cross-Frontier Report: Dark Matter

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Executive Summary

The evidence for Dark Matter (DM) is overwhelming, yet the fundamental nature of its constituents remains a mystery. Over the last decade, we have built a powerful and diverse collection of tools to unlock this mystery, both by refining established technologies and techniques and by harnessing new ones including artificial intelligence/machine learning (AI/ML) and quantum sensing/control. In parallel, we have continued to build our understanding of how DM shapes our universe. We are well-positioned for a great discovery.

From its production to its interactions, DM is a major science driver across all experimental Frontiers – Cosmic Frontier (CF), Energy Frontier (EF), Neutrino Frontier (NF), and Rare Processes and Precision Frontier (RF) – as well as the cross-cutting Frontiers: Accelerator Frontier (AF), Community Engagement Frontier (CEF), Computational Frontier (CompF), Instrumentation Frontier (IF), Underground Facilities (UF) and Theory Frontier (TF). Because the science of DM does not respect Frontier boundaries, a unified strategy is needed to maximize discovery potential.

Complementarity Within and Across Frontiers

Complementarity drives discovery in multiple ways. The space of viable DM candidates and their properties is large, and a single experimental technique or approach cannot be used to test all the possibilities; a diverse range of techniques provides access to a much broader ensemble of DM scenarios. Where different approaches have simultaneous sensitivity to a particular DM candidate, they provide essential and complementary information and promote healthy competition.

Some techniques can tell us whether a new particle constitutes the bulk of the DM in the Galactic halo while others may better elucidate interactions of DM with known particles, with a third category mapping the spectrum of new "dark sector" particles related to the DM. In the event of a discovery, detection and exclusion by complementary techniques will help triangulate the fundamental nature of DM.

Maximize Opportunities for Discovery: Delve Deep, Search Wide

Embracing the role of complementarity, the DM community proposes a strategy to *delve deep and search wide* to maximize discovery potential. A range of highly compelling theoretical targets arising from simple/minimal models are accessible in the next decade via planned and proposed CF, EF, NF, and RF experiments, colliders, and observatories. While discovering the fundamental nature of DM is the ultimate

prize, searching in these regions and *not* finding DM would provide important information on the properties of DM. Simultaneously, our strategy encompasses the development of new technologies and techniques to explore new possibilities and complement the sensitivity of existing searches.

Discovery Strategy
The community puts forth the following strategy for discovering the fundamental nature of DM:

- **Build a portfolio of experiments of different scales:** Experiments at all scales are needed to untangle the mystery of DM and cover the very broad range of theoretically motivated parameter space. Existing and planned large-scale facilities across the HEP Frontiers have exceptional potential to discover fundamental properties of DM. We should commit to scaling up mature technologies that can promise significant sensitivity improvements, developing potentially transformative new technologies to maturity, and supporting efforts to maximize and make accessible large projects' science output in the search for DM. At smaller scales, execution of the existing Dark Matter New Initiatives (DMNI) program and similar future calls are necessary to build the most compelling DM portfolio, develop experience in project execution, and accelerate the pace of discovery.

- **Leverage US expertise in international projects:** The effort to understand the fundamental nature of DM is a world-wide endeavor. Coordination and cooperation across borders is critical for enabling this discovery. While building a strong US-based program, we should pursue opportunities to leverage key US expertise as a collaborative partner in international projects and play a leadership role in this critical area.

- **Provide support to further strengthen the theory program:** A strong theory program is essential to make connections between experimental Frontiers and take full advantage of new developments in analysis techniques. Theorists' input has been and will be critical for developing innovative new approaches to better understand and detect DM, and for determining how to predict and relate signals across a range of experimental probes.

- **Support inter-disciplinary collaborations that enable discovery:** Many searches for DM benefit greatly from cross-disciplinary expertise, with examples ranging from nuclear physics to metrology, and astrophysics to condensed matter and atomic physics. Mechanisms to support such inter-disciplinary collaborations should be established.

- **Targeted increase in the research budget:** New research funding targeted toward solving the DM problem is essential to enable new ideas, new technologies, and new analyses. The number of active efforts exploring DM has increased tremendously in the past decade, without a concomitant increase in research funding. Across all Frontiers and project scales, research funding is critical to enable discovery and build on new capabilities, both in projects focused specifically on DM and to support DM analyses at multi-purpose experiments. Without such support, the community will not be able to execute the program described here, decreasing the chances of solving the mystery of DM.

13.1 Introduction

Determining the fundamental nature of dark matter (DM) is one of the major open questions that confronts our understanding of physics, and it has been among the guiding themes of the Snowmass process in most HEP Frontiers. While the microscopic properties of DM remain almost completely unknown, the relatively similar energy densities of dark and visible matter in the Universe — DM has five times more energy density than visible matter — is suggestive that there may be non-gravitational interactions between DM and the Standard Model (SM). However, the nature of these interactions is essentially unconstrained, necessitating a broad and comprehensive approach to this question to make progress in the next decade. This challenge

requires expertise, results, and planning from the full range of communities involved in the Snowmass 2021 process, across all Frontiers.

The 2013 Snowmass process had a topical group (CF4) specifically devoted to the complementarity of different DM studies. The white paper produced by that group, *"Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond,"* [1] reviewed existing and planned DM efforts in direct detection, indirect detection and collider experiments, as well as in astrophysical probes.

The need for diverse and complementary approaches to the DM problem is even more pressing now than it was in 2013. The DM search domain has broadened significantly with promising new avenues now under development that will yield results in the next decade. Our theoretical understanding of possible DM parameter space has grown, and that space is being explored by a much larger number of projects at different scales. Working in tandem, experiment, observation, theory, and computation have the potential to identify key DM properties while definitively excluding vast swathes of parameter space.

This document re-casts the scope and definition of complementary approaches to DM identification to reflect the current state of the field (Section 13.2), summarizes the needs of the different communities looking for DM and their complementary strengths (Section 13.3), and supports these arguments with cross-Frontier case studies (Section 13.4). An extended version of this report is also available [2].

13.2 Dark matter complementarity in the coming decade

A complementary ensemble of DM searches is key to a comprehensive strategy, with advantages including:

1. Different approaches to DM searches allow us to probe different fundamental properties of the DM. For this reason, complementary approaches will be necessary to fully identify the DM and understand its physics. For example, cosmological and astrophysical probes allow access to environments not found on Earth and time/space scales dwarfing terrestrial experiments, and consequently have unique sensitivity to a range of properties including the DM lifetime, annihilation rate, and self-interaction cross section. Rare interactions between DM and the SM are often most precisely probed in terrestrial experiments, which enjoy controllable and clean environments. DM production could be observed in extreme environments in the Cosmic Frontier, or under controlled laboratory conditions at accelerators and colliders in the Energy, Rare Processes and Precision, and Neutrino Frontiers; such measurements can reveal DM interactions in energy domains beyond those of the halo DM, including its early-universe behaviour and any dark sector particle spectrum beyond DM. This kind of complementarity is showcased in the case studies *Minimal WIMP Dark Matter*, involving the Energy and Cosmic Frontiers, *Sterile Neutrino Dark Matter*, involving the Cosmic and Neutrino Frontiers, and *Wave-like Dark Matter: QCD Axion Discovery*, involving the Cosmic, Neutrino, and Rare Processes Frontiers.

2. Different approaches to DM searches offer unique discovery sensitivity to distinct scenarios and regions of parameter space. Only by performing a variety of experiments, covering multiple Frontiers, can we span the wide DM parameter space. For example, DM interactions with the SM may be either suppressed or enhanced at low energies; to maximize the chances of a discovery, it is important to support both experiments sensitive to non-relativistic DM signals and those that explore the physics of DM at higher (often relativistic) energies. This kind of complementarity is also explored in the case study *Generic BSM-mediated and Vector Portal Dark Matter*, involving the Energy and Rare Processes and Precision Frontiers.

3. Results from any one class of searches can continuously inform the interpretation of other measurements. A Cosmic Frontier detection of relic DM would connect any observed candidate

to the cosmological evidence that motivates the entire DM program, and provide a target and motivation for future efforts in other Frontiers. Combining results obtained with different approaches can address otherwise-intractable uncertainties — e.g. DM production probes are independent of the fraction of DM due to a particular candidate, or the DM distribution. Complementary measurements can also reduce systematic uncertainties directly: as two examples, cosmic measurements of the density and velocity distribution of DM are essential for the interpretation of direct and indirect searches, and accelerator experiments can constrain cosmic ray physics relevant for indirect searches [3].

4. Different DM experiments can be co-located and/or profit from the same or similar technological infrastructure. Efficient use of shared resources enables a wider exploration of DM. Examples include small Rare Processes and Precision Frontier accelerator experiments that can be co-located with Energy Frontier collider experiments, using the same high-energy beams to produce different kinds of DM. Such experiments are discussed in the Rare Processes and Precision Frontier and their connection to collider experiments is discussed in the Energy Frontier report [4].

The community searching for DM has grown much more diversified in terms of technologies, search targets, and project scales. Since the last iteration of Snowmass in 2013, many new approaches to searching for DM, as well as new theoretical hypotheses, have attained sufficient maturity to be part of the toolkit that we will use to make progress in the quest for DM in the next decade. The older approach to DM complementarity (as outlined in the previous Snowmass whitepaper [1]) focused primarily on the Weakly Interacting Massive Particle (WIMP) hypothesis and direct DM-SM interactions, and incorporated high-mass new particle searches, direct and indirect detection, and astrophysical probes. This remains an important hypothesis that should be rigorously tested as part of a program that "delves deep." However, the WIMP is now joined by a greater diversity of alternative DM candidates. The QCD axion has emerged as another key target for a focused suite of experiments that will enable a definitive search for this candidate. Candidates and possible signatures that inform the wider strategy include light particle-like DM with masses in the MeV-GeV range, wave-like DM in addition to the QCD axion (such as ultralight scalar or vector bosons), signatures of the greater dark sector including long-lived particles, cosmological observations of DM properties on large scales, and new signatures of DM in gravitational waves and other multi-messenger observations.

The strategy presented above was developed from the bottom-up through the communities represented by the Frontier Topical Groups. It is well-aligned with the Basic Research Needs for Dark Matter Small Projects New Initiatives report [5], which highlighted the growing landscape of smaller experiments to produce and detect DM at accelerators, as well as the direct detection of light and ultra-light DM. The goal of the following sections is to summarize the needs of the individual Topical Groups and show that the needs are highly complementary as are the techniques. A common strategy across HEP is needed to enable the discoveries that will reveal the nature of DM.

13.3 Realizing dark matter complementarity across Frontiers

In this section, we briefly summarize the main approaches towards identifying the fundamental nature of DM from each Snowmass Frontier, referring to the Topical Group whitepapers for further information and needs.

Cosmic Frontier 1 - Direct and Indirect Searches for Particle Dark Matter. Direct detection experiments using mature technologies, like large liquid noble detectors, probe some of the smallest cross sections ever measured in the non-relativistic regime — favorable for models where interactions are enhanced

at low velocities — and provide leading sensitivity to heavy DM up to ultraheavy mass scales. A new era of technological development has enabled sensitivity to tiny energy depositions of eV-scale and below, opening up sensitivity to unexplored parameter space for DM masses below 1 GeV. Indirect detection provides a model-independent probe of the minimal thermal relic scenario with s-wave annihilation, with expected sensitivity up to tens of TeV masses in the next decade, and constraints of some form up to the Planck mass. Such searches provide unique probes of the DM decay lifetime (and other long-timescale processes), via their access to distance and time scales that dwarf any terrestrial experiment, and cover enormous mass ranges.

The next decade offers a broad array of exciting opportunities in direct and indirect detection, as discussed in Ref. [3]. To pursue these opportunities requires a diverse, continuous portfolio of experiments that includes both direct and indirect detection techniques at multiple scales. Moderate- and large-scale experiments allow us to delve deep into high priority target scenarios such as WIMPs, whereas an ensemble of small-scale experiments like those supported by the Dark Matter New Initiatives (DMNI) program provides versatility and the ability to test an expanded range of models. Support for theory, simulations, calibration, background modeling and complementary astrophysical measurements is essential to enabling discovery, as is R&D towards improved detector technologies. Lastly, direct detection experiments, particularly the next generation of WIMP searches, will require continued investment in underground facilities.

Cosmic Frontier 2 - Direct Searches for Axion Dark Matter. Wave-like DM encompasses all candidates with masses less than 1 eV. Due to their small masses, the detection principles are vastly different than those traditionally used in high energy physics. It is here where quantum measurement techniques become critical and advancements in this area have opened up a broad horizon of new candidates to explore and many opportunities for discovery. Within this group, the well-motivated QCD axion is an excellent DM candidate that also solves the strong CP problem. Building on the success of ADMX-G2, the new moderate-scale DMNI experiments ADMX-EFR and DMRadio-m^3 are readying to start construction. In the next decade, a portfolio of moderate-scale experiments are poised to explore significant QCD axion parameter space. A concentrated effort coupling R&D, demonstrator-scale experiments, and theory, would enable searches for a broader spectrum of candidates.

Cosmic Frontier 3 - Cosmic Probes of Dark Matter. Cosmic probes provide the only direct, positive empirical measurements of the existence and properties of DM. These probes complement terrestrial DM searches by constraining the interaction strength between DM and the SM in otherwise inaccessible regions of parameter space. In addition, cosmic probes provide the only known way to directly study the fundamental properties of DM through gravity, the only force to which DM is known to couple. Cosmic probes are sensitive to the DM mass, lifetime, self-interaction cross section, and other dark sector particles. In particular, cosmic probes are on the cusp of detecting DM halos that are devoid of baryonic galaxies, providing a strong test of the cold, collisionless DM paradigm.

The construction of future facilities spanning the electromagnetic spectrum, as well as gravitational waves, can provide sensitivity to DM physics, as well as the physics of dark energy and the early universe. Strategic HEP investments in the construction and operation of Rubin LSST, CMB-S4, and Spec-S5 should include DM physics as a core science driver to be considered during the design and operation of these experiments. Cosmic probes provide robust sensitivity to the microphysical properties of DM due to enormous progress in theoretical modeling, numerical simulations, and astrophysical observations. Theory, simulation, observation, and experiment must be supported together to maximize the efficacy of cosmic probes of DM physics.

Rare & Precision Frontier 6 - Dark Sectors at High Intensities. Intensity Frontier experiments offer unique access to the physics of low-mass DM by systematically probing a broad range of simple, well-motivated dark sectors neutral under SM forces. Near-term searches for *DM production* are needed to thoroughly explore the coupling ranges motivated by MeV-to-GeV thermal DM. Because the energies probed in Rare & Precision Frontier experiments are similar to those relevant for light DM thermal freeze-out, the range of production cross-sections expected for low-mass thermal relics is compact—and accessible—regardless of the DM spin. In DM models where interactions are suppressed at low velocities, cosmological and Galactic DM signals can be suppressed by orders of magnitude. Thus, accelerator-based production is the favored path to detection of these scenarios. Intensity Frontier experiments can also discover and characterize *light dark-sector particles that decay into SM particles*, often with detectably long lifetimes. Such particles arise in most generalized freeze-out scenarios such as strongly interacting massive particles, forbidden DM, and secluded DM [6]. Their discovery can shed light on the interactions, nature, and origin of DM. Both goals, searching for DM production and for visibly decaying particles related to DM, were called out in the 2018 DM New Initiatives Basic Research Needs report [5].

Achieving these goals over the next decade requires a four-pronged approach: performing dark-sector analyses at multi-purpose experiments; realizing the experiments selected through the competitive DMNI program; broadening the DMNI experimental portfolio to achieve the goals laid out in the DMNI Report, including a focus on signatures of long-lived dark sector particles decaying (semi)visibly; and continued investment in dark-sector theory.

Energy Frontier 10 - Dark Matter at Colliders. Present and future colliders [4, 7] can search for particle DM and its interactions, covering a broad swath of scenarios ranging from the canonical WIMP to more general models of DM particles and the mediators of their interaction or extended dark sectors. They can detect invisible particles produced in collisions via missing transverse momentum, but their greatest strengths are their ability to study how these invisible particles interact with other particles and to search for additional particles involved in the DM physics.

Over the next decade, the High-Luminosity LHC (HL-LHC) can explore whether DM couples to the Higgs boson or other beyond the Standard Model (BSM) portal particles, and test supersymmetric and other particle DM candidates that have been long-term targets of the field. On longer timescales, an electron-positron collider can push this sensitivity significantly further, as well test DM models that favor couplings to leptons. A hadron or muon collider would allow direct exploration of far-higher energy scales, with the greatest prospects to discover WIMP multiplets, and kinetically-mixed thermal DM above a GeV.

High-energy colliding beam facilities can also be used for special-purpose, co-located DM experiments searching for long-lived, dark sector particles. An example is the case of the proposed Forward Physics Facility [8] for the HL-LHC, but similar facilities would provide similar capabilities at other future colliders.

Neutrino Frontier 3 - Dark Matter in Neutrino Experiments. The high power beams, multi-kiloton scale far detectors underground, and near detector systems needed for precision neutrino experiments make a broad variety of BSM searches possible in the Neutrino Frontier. The high power proton beams can produce dark sector particles, such as axion-like particles, light DM and heavy neutral leptons, which can be detected in the precision near detector complex. Dark sector particles with oscillatory behavior, e.g. sterile neutrinos, can be probed in the far detector in combination with the near detector complex in long baseline neutrino experiments. Dark sector particles that alter neutrino fluxes from natural sources, or those with cosmogenic origins such as boosted DM, can be detected in the underground, massive far detectors.

Such rare dark sector interactions can be easily masked by backgrounds from a variety of sources, such as cosmic rays, terrestrial radioactive sources, and neutrino interactions. The current level of understanding of neutrino-nuclear interactions as well as neutrino spectra from natural sources is insufficient to effectively estimate or control them to the precision necessary for longer term dark sector particle searches, necessitating a strong synergistic and sustained collaboration between the nuclear physics and high energy physics communities to perform measurements needed to improve the modeling of neutrino-nuclear interactions, such as the *e*4nu collaboration.

Theory Frontier. The allowed mass ranges and interactions for DM are so vast that it is impossible to undertake any meaningful exploration of this parameter space without insight from theory. Theory is the language needed to make sense of results from different experiments and Frontiers [9]. Broadly, theory complements and enhances experimental DM searches in three ways:

Theory is essential to *define connections between experimental programs and understand their complementarity* in the context of specific DM models. This role broadens the impact of null results, and becomes crucial in understanding and verifying a potential signal.

Theory can *motivate experimental programs* for DM searches by tying DM to other deep questions and insights about particle physics. Examples include the hierarchy problem (a central problem of the Energy Frontier) inspiring WIMP DM, neutrino mass generation (a central problem of the Neutrino Frontier) inspiring sterile neutrino and neutrino-portal DM, and the strong CP problem giving birth to axion DM.

Theory can also *enable new paths to DM detection*, identifying DM scenarios accessible to ongoing experiments or even leveraging new technologies, experimental capabilities, and insights to define new experimental directions. Recent examples of such interplay are found throughout the DMNI program across Rare Processes and Cosmic Frontiers.

Instrumentation Frontier. Advances in instrumentation support every aspect of the hunt for DM, with new technologies often opening new regions of parameter space for exploration. Two examples in direct detection are in quantum sensors and noble element detectors. Rapid progress in quantum sensors over the past decade has been key in the success of the wave-like DM program. Such sensors come in a wide range of technologies: atom interferometry, magnetometers, calorimeters, and superconducting sensors to name a few. In searches for WIMP-like DM, the development of liquid noble detectors has paved the way for the huge strides in sensitivity seen since the last Snowmass, with LXe detectors leading the way and LAr close behind. Of course, there are many more examples that enable DM searches in all the Frontiers, including development in photon sensing, timing, calorimetry, etc. Continued R&D into instrumentation, development of the technical workforce, and tools to share common knowledge will be an important component of the future DM program. More information can be found in the Instrumentation Frontier report [10].

Computational Frontier. Computing and software are critical components of any search for DM, from the collection and storage of raw data, through various stages of data movement, data processing and data analysis, all the way to the interpretation of results. Interestingly enough, the majority of DM searches are rapidly converging towards exascale datasets that are not matched by technological developments and budgets [11–14]. Given this dramatic escalation in data volume and complexity, common computing needs can be identified to enable successful DM searches across all Frontiers, including: stronger partnerships with the national supercomputing facilities, lowering the barrier of entry and providing input on architecture evolution; scalable software infrastructure tools across HEP, avoiding duplication of effort; simulation tools

that are efficient, well-maintained, well-understood, and thoroughly validated; and industry collaborations on machine learning techniques, leveraging access to external experts.

An additional challenge specific to complementarity is the need to exchange data between different experiments and even Frontiers, which implies the necessity to converge on data formats and analysis tools. The DM community should take the lead in advocating for widely-adopted data and software standards, in support of global analyses of experimental results. Complementarity studies would be strengthened by an Open Science paradigm including both data and software, with the added benefit of enhancing the credibility of our potential discoveries, since progress in the field of DM will require thorough scrutiny of data and results.

Underground Facilities. Most DM direct detection experiments must be sited in underground facilities to evade cosmic ray backgrounds, and multiple new underground DM experiments are expected and being planned (at both large and small scales). Currently, underground facilities are largely subscribed by existing projects, with only limited space available in the coming years. There is, then, a clear need for additional underground space, tailored to the needs of DM experiments. This underground space must accommodate experiments across scales, including large liquid noble or freon experiments and smaller installations, for example mK facilities. Assembly of future experiments will occur largely in the underground environment, requiring underground radon-free clean rooms. Given the volume of gas/cryogen, future liquid noble experiments also require underground areas for staging (e.g., gas storage) and utilities (e.g. pumps, distillation). These new suitable spaces must be available by the late 2020s to meet the demand, which may be met in North America by proposed new excavations at SURF or SNOLAB. More information can be found in the UF report [15].

Accelerator Frontier. Current and future accelerator facilities are the underpinning of both Intensity Frontier and Energy Frontier searches for DM and dark sectors. Several beam facilities for axion and DM searches have been shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAR (a 1 GeV, 100 kW PIP-II Accumulator Ring). In general, we should efficiently utilize existing and upcoming facilities to explore dedicated or parasitic opportunities for rare process measurements — examples include the SLAC SRF electron linac, MWs of proton beam power potentially available after construction of the PIP-II SRF linac, spigots of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC. At the Energy Frontier, an e^+/e^- Higgs Factory (e.g. FCC-ee, C3, etc) will likely be the next major accelerator facility; interest in discovery machines such as O(10 TeV c.m.e.) muon colliders has also gained significant momentum. These machines' open-ended discovery potential includes sensitivity to a range of particle DM scenarios. More information can be found in the AF report [16].

Community Engagement and Workforce Development for Dark Matter. The last two decades have seen an explosion in the number of physicists engaged in DM detection, and the enthusiasm for the topic has been palpable throughout Snowmass 2021. In order to support this enthusiasm, the community needs to enhance its engagement efforts at all levels of society, most notably with the education system, industry partners, and policy makers. Outreach widens access to information, and the exciting mystery of DM acts as a powerful recruiting tool for HEP.

Career pipeline and development are crucial to sustaining such an expansion, which in turn requires a renewed focus on the diversity, equity, inclusion, and accessibility of the field. The historical exclusion of marginalized people from high energy physics is fundamentally harmful to the humanity of individuals who are excited and curious about science. Moreover, creating equal opportunity and equality in particle

physics is essential to professional success in our field, ensuring breadth of perspectives and a deep talent pool. Developing a broad talent pool sustains both scientific advancements and the democratic principle of publicly supported and engaged activities.

Equal opportunities in HEP go hand in hand with more traditional priorities. The search for DM is highly interdisciplinary and is therefore an excellent training ground for our next generation of scientists. DM searches that rely on quantum sensing and AI/ML align with the need for training in these areas both in HEP and beyond. The long gaps between design and commissioning of large-scale HEP projects such as future colliders can lead to leaks in the pipeline of key knowledge holders. Small- and medium-scale DM projects can bridge these gaps, training scientists across all experimental phases, from design to construction to commissioning and analysis. Thus, beyond their scientific merits, these projects sustain expertise in hardware development, construction, and their interface with science delivery, benefiting the field overall. The Community Engagement Frontier report [17] addresses these and other workforce questions.

13.4 Case Studies

Fig. 13-1 provides a graphical summary of the breadth of theoretical scenarios that can provide DM candidates. The possibilities span enormous ranges in DM mass and interaction strength.

In the case studies below, we briefly discuss several scenarios to illustrate how complementarity between DM searches could enable discovery of the fundamental nature of DM and allow triangulation of its properties. More detailed versions of these scenarios may be found in Ref. [2]. Additional relevant case studies may be found in Refs. [5, 18].

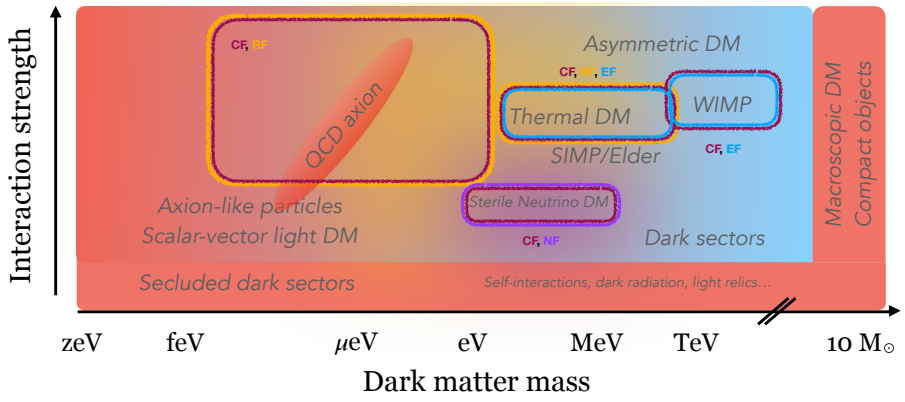

Figure 13-1. *Summary of case studies presented in this document, shown in the context of a sketch of the coupling-mass plane including the parameter space typical of some of the rich variety of DM theories possible. The shaded colors in this sketch are suggestive of the Frontiers with experiments represented in the case studies in a given region, with color coding specified near the rounded rectangles.*

Minimal WIMP Dark Matter. One of the simplest possibilities for DM involves a new particle multiplet that interacts with SM particles via the weak interaction [19]. Accidental or imposed symmetries lead to the stability of the lightest particle of this multiplet, providing a suitable DM candidate. The two most-widely studied scenarios are the cases where the DM is part of a Dirac fermion doublet (called the Higgsino) or of a Majorana fermion triplet (Wino); these multiplets appear in supersymmetric (SUSY)

theories as superpartners of the SM Higgs/gauge bosons, and so the cases where the DM is close to "pure Higgsino" or "pure Wino" can be realized in specific regions of the broader parameter space of SUSY theories.[1] Such scenarios are very predictive, with the only free parameter being the DM mass, and this can also be fixed (at 1.1 TeV for the Higgsino and 2.8 TeV for the Wino) by matching the relic density under the assumption of a standard cosmology with thermal freezeout of the DM [20, 21].

Indirect searches for gamma-rays and antiprotons already constrain the thermal Wino (e.g. [22, 23]), albeit with significant systematic uncertainties associated with the DM density and cosmic-ray propagation. Future cosmic probes and complementary astrophysical measurements could reduce these uncertainties and strengthen the bounds. In direct detection, the cross section is very small [24], but large future direct detection experiments such as DARWIN can probe the Wino scenario, with cross-sections still above the neutrino fog [25]. The direct detection cross section for the thermal Higgsino lies in the neutrino fog, but CTA should have sensitivity to the indirect-detection signal [26]. Current colliders can only probe lighter non-thermal Wino- and Higgsino-like particles, but a future multi-TeV lepton or hadron collider could meet the thermal target for both Wino and Higgsino (and eventually even for larger multiplets) [20, 21]. A direct or indirect detection during the planning phase of such a collider would provide crucial input to the design. A collider discovery would provide in-depth information on the WIMP's interactions with SM particles and its associated particle spectra. Alternatively, null results at collider experiments could significantly constrain the interpretation of a putative DM signal from direct or indirect detection.

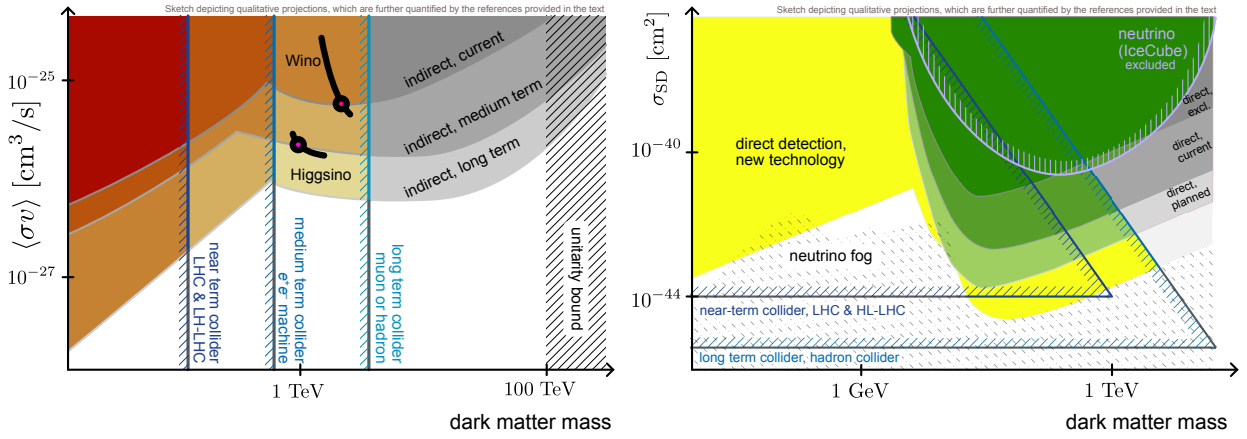

Figure 13-2. *Indicative sketches depicting qualitatively how future collider, indirect detection, and neutrino experiments (a) or collider and direct detection experiments (b) may complement each other during discoveries of Wino/Higgsino DM or of BSM-mediated DM, respectively. The y-axis indicates the annihilation cross section to example SM final states in (a) and the spin-dependent scattering cross section on SM targets in (b). Regions where "excluded" is mentioned in the figure have been covered by published results, while other areas depict approximate regions of sensitivity for current and future experiments. Regions of overlapping coverage, where complementary observations in both types of experiments would be possible, are indicated by saturated colors. Regions accessible by only one of the two types of experiments are shown in muted colors or grayscale.*

Generic Beyond the Standard Model (BSM)-mediated and Vector Portal Dark Matter. If DM particles are discovered by either Cosmic Frontier or accelerator-based (EF and/or RPF) experiments,

[1] Setting aside the connection to supersymmetry, which is not essential, many of the same general principles also apply to larger electroweak multiplets; for a discussion of other options see e.g. [20, 21].

the other technique will be essential to understanding its properties. In the case of a CF detection of DM particles, different types of cosmic probes and target materials can shed some light on the nature of DM interactions. However, producing the same kind of DM in the lab, with a known initial state, opens new windows to characterising DM interactions and resolving the roles of related, cosmologically unstable, particles. Likewise, while a signal of invisible particle production in a fixed target or collider experiment can be related to DM models, a simultaneous discovery in Cosmic Frontier experiments is needed to ascertain the cosmological nature of the DM candidate.

This kind of complementarity is illustrated by theoretical scenarios that extend the WIMP paradigm to include an additional particle beyond the SM that mediates interactions between DM and SM. These mediator particles can decay into both DM and SM particles; searches for each decay mode offer further insight into the DM-SM interaction. A thermal history for the DM candidates in the early universe can be attained depending on the coupling types and strengths of the mediator (or *portal*) particle, as well as on the mediator and DM particle masses. Specific realizations of these models are used as benchmarks in e.g. Refs. [4, 27–29]. Figures 13-2 (b) and 13-3 (a) illustrate complementarity across CF, EF and RPF experiments in terms of both opportunities for simultaneous discovery (CF1/EF10) and complementary discovery sensitivity (EF10/RF6); we also refer the reader to Fig. 1-1 and Case studies 1 and 2 of [5] for discussion of the CF1/RF6 complementarity for low-mass DM. Further insights into these and related portal DM models can be gained from MeV-energy indirect detection (CF1) and probes of DM self-interaction (CF3).

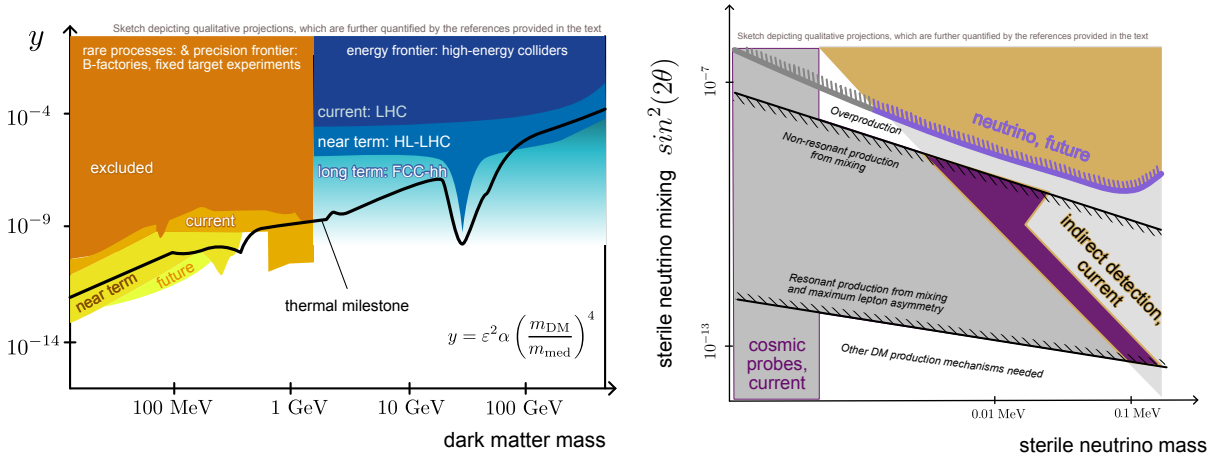

Figure 13-3. *(a) Sketch of how collider and accelerator experiments together can reach sensitivity across many orders of magnitude of DM mass to couplings expected for thermal-relic vector portal inelastic Dirac DM production (note: lepton colliders not shown). y parameterizes the DM-SM interaction strength and depends on the kinetic mixing parameter ϵ, dark-sector coupling α, and masses of the DM ($m_{\rm DM}$) and mediator ($m_{\rm med}$). (b) Sketch of constraints on the mass and mixing angle θ of resonantly produced sterile neutrino DM from indirect detection in X-rays, cosmic probes of small scale structure, and projected sensitivity of tritium beta-decay neutrino experiments.*

Sterile Neutrino Dark Matter. Figure 13-3 (b) is an illustration of the complementarity between cosmological, astrophysical, and laboratory searches for sterile neutrino DM (as compiled by [30]), with complementary reach provided by a combination of indirect DM searches (CF1; [3]), cosmic probes of structure formation (CF3; [18]), and laboratory neutrino facilities (NF3; [31]). Indirect detection

experiments searches for X-ray lines originating from the decay of keV mass sterile neutrinos. Current constraints come from Chandra, XMM-Newton, NuSTAR, INTEGRAL, and Fermi GBM observations of the various astrophysical systems (e.g., the Milky Way, M31, dwarf galaxies, and galaxy clusters) [32–39]. Future X-ray facilities such as *XRISM*, *Athena*, and the WFM instrument aboard the *eXTP* X-ray Telescope could increase sensitivity to mixing angle by orders of magnitude [40–43]. Cosmological constraints are due to the suppression of DM structure that occurs for producing keV-mass sterile neutrinos with a "warm" initial momentum distribution [44, 45]. These constraints will improve by orders of magnitude as measurements of the least massive DM halos improves with DESI [46], Rubin LSST [47], and future cosmological survey experiments [48]. Laboratory searches (e.g., Katrin, TRISTAN, BeEST, and HUNTER) [49–52] have different dependencies on the model behavior of sterile neutrinos in the early Universe (e.g., in cosmologies with large lepton asymmetry, low reheating temperature and/or neutrino non-standard interactions) making them highly complementary to indirect and cosmological searches [53, 54]. Below the lowest solid line, achieving the correct relic density of sterile neutrino DM requires other production mechanisms beyond active-sterile mixing; these generally involve heavy BSM particles, which can be probed at the Energy Frontier.

Wave-like Dark Matter: QCD Axion Discovery. The discovery of a QCD axion by a direct detection experiment such as DMRadio-m^3 with a mass $< 1\,\mu$eV can be used to illustrate of the wide-ranging implication of a wave-like DM discovery. The detailed spectral measurements from direct axion searches would almost instantaneously provide a measurement of the velocity distribution of DM in the halo. These measurements and subsequent measurements of the position distribution can then be compared to the results from cosmic probes of DM. Since axions with masses below $< 1\,\mu$eV imply additional fields at the time of inflation, CMB B-modes would then be out of range for next generation CMB experiments. A possible discrepancy between such measurements would open the door to significant changes in our understanding of particle physics and cosmology.

Most direct detection experiments use the axions' coupling to photons. A precision measurement of this coupling, or the coupling to other parts of the SM, can disentangle which category of QCD axion or axion-like particle has been discovered. There is complementarity here with other table-top precision measurements. The discovery of a QCD axion implies additional particles, e.g. KSVZ models predict additional quarks and DFSZ predict an expanded Higgs sector. Either would be strong motivation for higher-energy colliders and would guide the design of such efforts.

13.5 Conclusions

DM presents a fundamental puzzle to particle physics. The space of viable, theoretically-motivated candidates is enormous and multi-dimensional, spanning many orders of magnitude in mass and interaction strength. To make progress on this challenging problem, maximize the chances of a transformative discovery, and fully elucidate the properties of DM and related new physics in the event of such a discovery, we advocate for a cross-Frontier effort incorporating multiple complementary approaches to the problem. The suite of approaches discussed in this summary, and in the various topical group and Frontier reports, will allow us to delve deep into highly compelling, long-standing, and well-studied scenarios for the nature of DM, and simultaneously to open up our search to a wide and less-explored space of exciting and well-motivated possibilities. A decade of coherent cross-Frontier DM exploration is an opportunity that should not be missed.

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Conclusion and Acknowledgements

Snowmass 2021 was a scientific study which provided an opportunity for the entire U.S. particle physics community, in consultation with its international partners, to come together to identify and document a scientific vision for the future. Snowmass 2021 succeeded due to the contributions of the individual scientists who participated, and through the process of discussion and collaboration which took place. The Snowmass process included many preparatory meetings on various topics, and during the process members of the community submitted more than five hundred scientific white papers for consideration. The input gathered was summarized in the reports of about eighty topical subgroups, and all of this information was considered collectively by over a thousand members of the community in a ten-day workshop held at the University of Washington in July, 2022. Subsequently, each topical area integrated the information received into ten Frontier Summary Reports and a Report from the Snowmass Early Career group. Subsequently, the Frontier and Early Career reports were distilled into the summary chapter and executive summary included in this volume.

The documents included in this book, and the white papers and reports from which they are derived, are the output of Snowmass 2021. Together, these documents provide a comprehensive view of particle physics at the beginning of 2023 as viewed by the U.S. High-Energy Physics community. Collectively, this information will provide input to the 2023 Particle Physics Prioritization Panel (P5) subpanel of the U.S. High-Energy Physics Advisory Panel (HEPAP), and will help to guide and inform the activity of the U.S. particle physics community during the coming years.

Several thousand people participated in Snowmass 2021 and helped to make it a success. Since there are too many people to thank individually, here we acknowledge the people who served on the main committees/groups that helped coordinate and organize the overall activities of Snowmass 2021. Since these committees were in place and functioning by 2020, and in some cases by 2019, we tried to include everyone, even those that rotated off or onto the committees in mid-course and therefore served only part of the time. We apologize if we omitted someone.

We wish to thank the following people who provided advice, direction, and guidance to Snowmass 2021 through their participation in the following all- Snowmass working groups and committees. We also express our gratitude to many others who played similar roles in organizing activities such as meetings, lecture series, and forums in the Frontiers.

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The Snowmass Advisory Group:

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The Snowmass Frontier Conveners:

Accelerator Frontier: Stephen Gourlay[13], Tor Raubenheimer[19], Vladimir Shiltsev[1]; **Community Engagement Frontier:** Kétévi A. Assamagan[14], Breese Quinn[33]; **Computational Frontier:** V. Daniel Elvira[1], Steven Gottlieb[20], Oliver Gutsche[1], Benjamin Nachman[13]; **Cosmic Frontier:** Aaron S. Chou[1], Marcelle Soares-Santos[34], Tim M. P. Tait[35]; **Energy Frontier:** Meenakshi Narain[36†], Laura Reina[16], Alessandro Tricoli[14]; **Instrumentation Frontier:** Phillip S. Barbeau[37], Petra Merkel[1], Jinlong Zhang[32]; **Neutrino Frontier:** Patrick Huber[38], Kate Scholberg[37], Elizabeth Worcester[14]; **Rare Processes and Precision Measurements Frontier:** Marina Artuso[39], Robert H. Bernstein[1], Alexey A. Petrov[40]; **Theory Frontier:** Nathaniel Craig[41], Csaba Csáki[42], Aida X. El- Khadra[9]; **Underground Facilities and Infrastructure Frontier:** Laura Baudis[43], Jeter Hall[44], Kevin T. Lesko[13], John L. Orrell[45].

Snowmass Early Career (SEC):

Young scientists faced severe challenges during the COVID pandemic. Nevertheless, they managed to participate, organize activities, and have a real impact on outcome. Here we list the DPF executive Committee Members who took a coordinating role in the SEC:

Julia Gonski[18], Fernanda Psihas[1], Sara M. Simon[1]

We want to thank all the participants in the SEC for their superb effort under difficult circumstances that particularly a ected young scientists.

Snowmass Community Planning Meeting:

We want to thank the following people who helped organize the Snowmass Community Planning Meeting (CPM), originally planned as an in-person meeting, but, because of the pandemic, became an all-virtual meeting from Oct. 5-8, 2021:

Bo Jayatilaka (co-chairperson)[1], Brendan Kiburg (co-chairperson)[1], Jonathan Asaadi[46], Saptaparna Bhattacharya[3], Zoltan Gecse[1], Shih-Chieh Hsu[17], Erica Snider[1], Tiziana Spina[1], Gordon Watts[17], Yuanyuan Zhang[47].

Snowmass Community Summer Study and Workshop:

We especially want to thank the following people who contributed to the success of the Snowmass Community Summer Study and Workshop (CSS), the final meeting of Snowmass 2021, at the University of Washington (UW) in Seattle, from July 17-26, 2022.

CSS Program Committee: Gordon Watts (co-chairperson)[17], Shih-Chieh Hsu (co-chairperson)[17], Joel N. Butler (co- chairperson)[1], R. Sekhar Chivukula[2], André de Gouvĕa[3], Tao Han[4], Young-Kee Kim[5], Priscilla Cushman[6], Glennys R. Farrar[7], Yury G. Kolomensky[8], Sergei Nagaitsev[1,5], Nicolás Yunes[9], Kétévi A. Assamagan[14], Phillip S. Barbeau[37], Nathaniel Craig[41], Benjamin Nachman[13], Meenakshi Narain[36†], John L. Orrell[45], Alexey A. Petrov[40], Vladimir Shiltsev[1], Tim M. P. Tait[35], Eiizabeth Worcester[14], Garvita Agarwal[48], Jacob Zettlemoyer[1]; **CSS Local Organizing Committee:** Gordon Watts (UW, co-chairperson)[17], Shih-Chieh Hsu (UW, co-chairperson)[17], Quentin Buat[17], Alvaro E. Chavarria[17], Jason

[†]deceased, January 1, 2023.

Detwiler[17], Joey Shapiro Key[17], Alejandro Garcia[17], Anna Goussiou[17], Laura Jeanty[49], Henry Lubatti[17], Elise Novitski[17], Gray Rybka[17], Jan Strube[45,49], Lauren Tompkins[15], Tien-Tien Yu[49], Tal van Daalen[17], Mason Profitt[17].

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A final thanks to the participants:

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A

Glossary

Writing about particle physics is full of acronyms and other puzzling terms, most of which are not easily deciphered even by experts in other areas of particle physics. For the benefit of the readers of this book, we define many of these terms here. Some acronyms are defined using other acronyms. In those cases, please find the definitions of those acronyms at the appropriate place in this list.

$0\nu\beta\beta$: Neutrinoless double-beta decay, a nuclear decay process in which two electrons and zero neutrinos are emitted.

$2\nu\beta\beta$: Double-beta decay, a nuclear decay process in which two electrons and two neutrinos are emitted.

2HDM : Two-Higgs-Doublet Model, a model with two Higgs fields, usually with natural flavor conservation in Higgs boson couplings.

AAAS : American Association for the Advancement of Science.

AC-LGAD : AC-coupled **LGAD**.

ACTA : Augmented Cherenkov Telescope Array, the next-generation atmospheric Cherenkov telescope project for gamma ray detection.

ADMX : Axion Dark Matter Experiment, an experiment at the University of Washington searching for axions using a large electromagnetic cavity in a static magnetic field.

ADMX-EFR : **ADMX**-Extended Frequency Range.

AdS : Anti-de Sitter space, a space-time background essential to many mathematical physics investigations.

AGILE : Astro-Rivelatore Gamma a Immagini Leggero, a space-based X-ray and gamma ray observatory.

AGN : Active Galactic Nucleus.

AI : Artificial Intelligence.

AIP : American Institute of Physics.

ALPHA : Axion Longitudinal Plasma Hodoscope.

ALCF : Argonne Leadership Computer Facility.

ALICE : A Large Ion Collider Experiment, an experiment at the **LHC** focusing on heavy ion collisions and the quark-gluon plasma.

ALP : Axion-Like Particle.

ALTIROC : **ATLAS** timing **ASIC**.

ALPS, ALPS-II : Any Light Particle Search, a series of experiments at **DESY** searching for **axions** and similar particles using laser light conversion in a strong magnetic field.

AMANDA : Antarctic Muon and Neutrino Detector Array, the first-generation neutrino telescope experiment in Antarctica.

AMF : Advanced Muon Facility, a proposed accelerator complex at **Fermilab** providing intense muon beams.

AMO : Atomic, Molecular, Optical

AMR : Adaptive Mesh Refinement.

AMS, AMS-02 : Alpha Magnetic Spectrometer, an antimatter detector located on the International Space Station.

ANITA : Antarctic Transient Antenna, a balloon experiment in Antarctica for detection of radio signals of ultra-high-energy neutrino events.

ANL : Argonne National Laboratory.

ANTARES : Astronomy with a Neutrino Telescope and Abyss environmental RESearch, a neutrino telescope experiment in the Mediterranean Sea.

APEX : A Prime EXperiment, an experiment at **JLab** searching for the production of dark photons using an intense electron beam.

API : Application Programming Interface.

APS : American Physical Society.

APS DPB : The American Physical Society Division of Physics of Beams.

APS DPF : The American Physical Society Division of Particles and Fields.

ARA : Askaryan Radio Array, a radiofrequency neutrino antenna experiment at the South Pole.

ARAPUCA : Argon R&D Advanced Program at UniCAmp, a light-trapping device for **LArTPC** detectors.

ARGO : A proposed future argon-based **Dark Matter** detector.

ArgoNeuT : Argon Neutrino Teststand, a small liquid argon **TPC** experiment at **Fermilab**.

ARIADNE : Axion Resonant InterAction Detection Experiment.

ARIANNA : Antarctic Ross Ice-shelf ANtenna Neutrino Array, a radiofrequency neutrino antenna experiment in Antarctica.

ART : An Intensity Frontier software framework developed by the **Fermilab** Scientific Computing Division and used by **NOvA**, **mu2e**, **Muon $g-2$**, **LArSoft** , **DarkSide**, **LArIAT**, and others.

A-Se : Amorphous Selenium.

ASIC : Application Specific Integrated Circuit, a silicon chip processor designed for a particular purpose.

ASTA : Advanced Superconducting Test Accelerator, an accelerator test facility at **Fermilab**.

ATCA : Advanced Telecommunications Computing Architechture.

ATF : Accelerator Test Facility, a user facility at **BNL** providing high-brightness electron and photon beams.

ATF, ATF2 : Accelerator Test Facility, an accelerator test complex at **KEK** built to study beam dynamics issues for the **ILC**.

ATLAS : A Toroidal LHC ApparatuS, a large experiment at the **LHC** optimized for high transverse momentum particle production.

ATR : Advanced Test Reactor, a research reactor at the Idaho National Laboratory.

Auger : Pierre Auger Observatory, experiment in Argentina that detects ultra-high-energy cosmic rays through both fluorescence and surface water Cherekov detectors.

Argonne Wavefield Accelerator, a beam facility at **ANL**.

Axion : A hypothetical, very light particle, with couplings to quarks that reverse under **P** transformations. Such particles could make up the **Dark Matter** of the Universe.

BaBar : An experiment at **SLAC**, using e^+e^- annihilation at approximately 10 GeV to study rare heavy quark and lepton decays.

Baikal : A neutrino telescope in Lake Baikal in Siberia.

Baksan : An underground laboratory in the Caucasus mountains in Russia.

BAO : Baryon Acoustic Oscillations.

Baseline : In neutrino physics, the distance between the neutrino production point, near an accelerator, and the neutrino detector.

BBN : Big Bang Nucleosynthesis.

BELLA : Berkeley Lab Laser Accelerator, a facility at **LBNL** for the development of laser-driven accelerators.

Belle : An experiment at **KEK**, using e^+e^- annihilation at approximately 10 GeV to study rare heavy quark and lepton decays.

Belle-II : An experiment at **KEK**, using e^+e^- annihilation at approximately 10 GeV to study rare heavy quark and lepton decays with 50-100 times the data set produced by **BaBar** and **Belle**.

BEPCII : Beijing Electron-Positron Collider II, an e^+e^- collider at **IHEP** with center of mass energy range of 2–4.63 GeV.

BESIII : An experiment at **IHEP**, using e^+e^- annihilation at approximately 3–4 GeV to study charm quark and tau lepton physics.

BEST : Baksan Experiment on Sterile Transitions, a proposed radioactive source experiment in Russia with a gallium detector.

BINP : Budker Institute for Nuclear Physics, a high-energy physics laboratory in Novosibirsk, Russia.

BMW : Budapest-Marseille-Wuppertal Collaboration carrying out lattice **QCD** calculations.

BNB : Booster Neutrino Beam, a neutrino beamline at **Fermilab** using the Booster.

BNL : Brookhaven National Laboratory.

Borexino : A solar neutrino experiment at **Gran Sasso**.

Boson : A type of elementary particle whose intrinsic spin is an integer (0, 1, 2, ...) multiple of $\hbar$. Such particles can make up a macroscopic force field such as the electromagnetic field.

BOSS : Baryon Oscillation Spectroscopic Survey, a galaxy survey aiming to measure baryon acoustic oscillations.

BR : Branching Ratio, the probability that an unstable particle decays to a particular final state.

BREAD : Broadband Reflector Experiment for Axion Detection.

BRN : Basic Research Needs, a process and set of workshops within the US **DOE** to obtain community input on priority technical goals and opportunities.

BSM : Beyond the Standard Model, a reference to new physics associated with an extension of the **SM**.

C : Charge conjugation, the interchange of particles and antiparticles.

CALICE : CALorimeter for Linear Collider Experiment, an experimental collaboration aimed at improving the technology of hadron calorimeters, especially with the **PFA** method.

Canfranc Underground Laboratory : An underground scientific facility in a former railway tunnel in the Spanish Pyrenees under Monte Tobazo in Canfranc, Spain.

Capability : In computing, a measure of high-speed, highly parallel computing that might require a large fraction of a supercomputer.

Capacity : In computing, a measure of computing in which many moderately parallel jobs are run alongside one another.

CAPTAIN : Cryogenic Apparatus for Precision Tests of Argon INteractions, a liquid argon R&D detector.

CASPEr : Cosmic Axion Spin Precession Experiment.

CAST : CERN Axion Solar Telescope, an experiment at **CERN** searching for **axions** radiated from the Sun.

CC : Charged Current weak interactions.

CCD : Charge Coupled Device, a class of pixel silicon detectors.

CDF : Collider Detector at Fermilab, a large experiment at the **Fermilab** Tevatron optimized for high transverse momentum particle production.

CDM : Cold Dark Matter, a class of **Dark Matter** models in which the dark matter particles move at nonrelativistic speeds.

CDR : Conceptual Design Report.

Ce-LAND : A ^{144}Ce source to be placed in **KamLAND** to study the reactor neutrino anomaly.

CEνNS : Coherent Elastic Neutrino-Nucleus Scattering, an **NC** neutrino process and also a proposed experiment to be sited at the **BNB**.

CE&O : Communication, Education, and Outreach, a topic of one of the "frontiers" in this study.

CEPC : Circular Electron Positron Collider, a large circular e^+e^- collider proposed to be hosted by China.

CERN : Conseil Européen pour la Recherche Nucleaire, the major European high energy physics laboratory, located in Geneva.

CESR : Cornell Electron Storage Ring, an e^+e^- colliding beam accelerator at Cornell University that operated in the energy range 3.5-12 GeV from 1979 to 2008. The accelerator is still in operation as a synchrotron light source (CHESS) and as an accelerator physics testbed.

CesrTA : CESR Test Accelerator, a configuration of **CESR** to study the design of electron damping rings, in particular, for **ILC**.

CFD : Constant Fraction Discrimination.

Chameleon : A new particle that has properties that depend on its environment.

CHIPS : CHerenkov detectors In mine PitS, a proposed experiment to use the **Fermilab** beams and massive Cherenkov detectors in flooded mine pits.

CHOOZ : A first-generation reactor neutrino experiment located in Chooz, France.

CKM : Cabibbo-Kobayashi-Maskawa matrix, the matrix relating the weak interaction and mass eigenstates of quarks.

CL : (Statistical) Confidence Level.

CLEAN : Cryogenic Low Energy Astrophysics with Noble gases, a cryogenic noble liquid experiment for **Dark Matter** and solar neutrinos.

CLEO : A general-purpose particle detector at **CESR** that studied heavy quark decays and spectroscopy.

CLFV : Charged Lepton Flavor Violation.

CLIC : Compact LInear Collider, a concept for an e^+e^- linear collider, with center of mass energies up to 3 TeV, based on two-beam acceleration.

CM : Center of Mass, the system for viewing a particle collision or decay in which the overall system is at rest.

CMB : Cosmic Microwave Background, the approximately isotropic microwave radiation in the universe created in the original formation of atoms from electrons and ionized protons.

CMB-S4 : Stage-IV **CMB** experiment.

CMD-3 : An experiment at **BINP** measuring the cross section for $e^+e^- \to$ hadrons.

CMOS : Complementary Metal-Oxide Semiconductor, a class of semiconductor devices.

CMS : Compact Muon Spectrometer, a large experiment at the **LHC** optimized for high transverse momentum particle production.

CoGeNT : COherent GErmanium Neutrino Technology, a germanium detector for **Dark Matter** and other signals requiring low background.

COHERENT : An experiment to measure **CEνNS** at the **SNS**.

COMET : An experiment at **J-PARC** searching for muon to electron conversion in the field of a heavy nucleus.

COUPP : Chicagoland Observatory for Underground Particle Physics, a **Dark Matter** detector using a bubble chamber, now located in the Sudbury Mine in Sudbury, Ontario.

CP : The combination of a **C** and a **P** transformation, converting particles to antiparticles, plus mirror (left-right) reflection. This is a very accurate, but not perfect, approximate symmetry of nature.

CPAD : Coordinating Panel for Advanced Detectors, an advisory panel on detector technology created by the **APS DPF**.

CPT : The combination of a **C**, and a **P**, and a **T** transformation, converting particles to antiparticles, plus mirror (left-right) reflection, plus reversal of the direction of time. Local quantum field theory predicts this to be a perfect symmetry of nature.

CPU : Central Processing Unit of a computer.

CRADA : Cooperative Research and Development Agreement, an agreement between a government laboratory and a private company to pursue R&D on a technology or project.

CSI : Coherent Scattering Investigations at the SNS, a proposed **CENNS** search experiment for the **SNS**.

CTA : Cherenkov Telescope Array, a planned large-area array of telescopes for high energy gamma rays.

CTF3 : CLIC Test Facilty 3, the most recent in a series of test accelerators for **CLIC** at **CERN**.

CUDA : Compute Unified Device Architecture, which defines a parallel computing architecture for NVIDIA **GPU**s.

CUORE : Cryogenic Underground Observatory for Rare Events, an experiment searching for neutrinoless double beta decay, located at **Gran Sasso**, Italy.

DØ : D-zero, a large experiment at the **Fermilab** Tevatron optimized for high transverse momentum particle production.

DAEδALUS : Decay At rest Experiment for δ_{CP} studies at the Laboratory for Underground Science, a neutrino oscillation experiment based on beams created by cyclotrons.

DAFNE : Double Annular Φ Factory for Nice Experiments, an e^+e^- collider at **LNF**.

DAMA : DArk MAtter experiment, a scintillator-based dark matter search experiment at **Gran Sasso**.

DAMIC : DArk Matter In CCD experiment, an experiment at **Fermilab** searching for light **Dark Matter** particles.

DANSS : Detector of the reactor AntiNeutrino based on Solid-state plastic Scintillator, a reactor neutrino experiment in Russia.

DAQ : Data Acquisition

Dark Light : An experiment at **JLab** searching for dark photons using an **FEL**.

Dark Matter : A type of matter not contained in the **Standard Model** and very weakly coupled to electromagnetism that makes up most of the matter in the universe.

Dark Sector : A set of particles neutral under the **Standard Model** forces and coupled only weakly to ordinary matter.

DarkSide : A **Dark Matter** search experiment at **Gran Sasso** using a liquid argon detector.

Daya Bay : A reactor neutrino experiment located near Daya Bay, China.

DC-DC converters : digital current to digital current converters.

DECam : Dark Energy Camera, used to conduct the **DES**.

Decay Constant : A parameter that determines the size of the matrix element for the decay of a hadron.

DeepCore : A low-energy extension to the **IceCube** experiment with a high density of photodetectors in a central region of the cube.

DEI : Diversity, Equity, and Inclusion.

DEIA : Diversity, Equity, Inclusion, and Accessibility.

DeeMe : Direact Emission of Electrons from Muon to Electron conversion, an experiment at **J-PARC** searching for neutrinoless muon to electron conversion

DES : Dark Energy Survey.

DESC : Dark Energy Science Collaboration.

DESI : Dark Energy Spectroscopic Instrument.

DESY : Deutsches Elektronen SYnchrotron, the major high energy physics laboratory in Germany, located in Hamburg.

Dichroicon : A Winston-style light concentrator built out of dichroic reflectors.

DIRC : Detection of Internally Reflected Cherenkov light, a detector using quartz bars for tracking and particle identification.

DIS : Deep Inelastic Scattering, a process of lepton scattering from a nucleon or nucleus with large momentum transfer, especially when only the lepton recoil is observed.

DJ-LGAD : Deep Junction **LGAD**.

DM : **Dark Matter**.

DMNI : Dark Matter New Initiatives, a DOE-supported program to fund small **Dark Matter** search experiments.

DOE : U.S. Department of Energy.

Double Chooz : A reactor neutrino experiment in Chooz, France, utilizing detectors at two distances from the source.

DPF : Division of Particles and Fields, a division of the American Physical Society.

DR : Dual Readout, a method for hadron calorimetry that corrects the charge/neutral response ratio by separate measurement of Cherenkov and scintillation light.

DREAM : Dual REAdout Method (**DR**)

Drive beam : A high energy particle beam used to create an electromagnetic field that can then accelerate another beam to high energy.

DS-LGAD : Double Sided **LGAD**.

DSNB : Diffuse Supernova Neutrino Background.

dSphs : dwarf Spheroidal satellite galaxies of the Milky Way.

DUNE : Deep Underground Neutrino Experiment, a next-generation long-baseline neutrino oscillation experiment, based at **Fermilab** and **SURF**.

E821 : Experiment at **BNL** to measure the anomalous magnetic moment of the muon; predecessor to **Muon $g-2$**.

E989 : **Muon $g-2$** Experiment at **Fermilab** to measure the anomalous magnetic moment of the muon.

EAS : Extensive Air Shower, produced by high energy cosmic rays in the Earth's atmosphere.

EBL : Extra-galactic Background Light.

eBOSS : Extended **BOSS**, program in **SDSS**-IV.

ECFA : European Committee for Future Accelerators

ECHo : Electron Capture ^{163}Ho experiment, a proposed neutrino mass microcalorimeter experiment.

EDM : Electric Dipole Moment.

eEDM : Electron **EDM**.

EFT : Effective Field Theory, a method of quantum field theory in which the effects of new particles or interactions that might be present at high energies are expressed by the addition of more complex operators to the equations of motion of the **SM**.

EIC : Electron-Ion Collider, an electron-proton and electron-heavy ion collider to be constructed at **BNL**.

EM : Electro-Magnetic.

EMPHATIC : Experiment to measure hadron scattering and production cross sections for improved neutrino flux predictions.

ENUBET : Enhanced NeUtrino Beams from kaon Tagging, a proposed project that aims to produce an artificial neutrino beam in which the flavor, flux, and energy of the produced neutrinos are known with unprecedented precision.

EP : Equivalence Principle.

ESA : European Space Agency.

ESS : European Spallation (neutron) Source, a future facility in Lund, Sweden.

ESSνSB : European Spallation Source Neutrino Super Beam, a proposal to use the **ESS** proton linac to generate a neutrino superbeam.

$\not\!\!E_T$: Missing Transverse Energy, unobserved momentum in a high-energy particle collision carried away by weakly interacting neutral particles.

ETROC : **CMS** timing **ASIC**.

Euclid : A dark energy space mission currently under development by the European Space Agency.

EVA : ExaVolt Antenna, a proposed balloon-based neutrino antenna experiment in Antarctica.

EW : ElectroWeak interaction, the unified description of the electromagnetic and weak interactions.

EWSB : ElectroWeak Symmetry Breaking.

Exascale : Of the order of 10^{18}, used in computing to refer to next-generation computation resources in memory or speed.

Exclusive decay : Particle decay to a specific, completely specified, final state.

EXO : Enriched Xenon Observatory, an experiment searching for neutrinoless double beta decay of the isotope Xe^{136}.

FACA : Federal Advisory Committee Act, the legislation that governs questions of openness and transparency for certain Federal committees. The act generally covers grant review panels of the **NSF** but not those of the **DOE**.

FACET, FACET II : Facility for advanced ACcelerator Experimental Tests, a user facility at **SLAC** for experiments on high-gradient electron accelerator technology.

FAIR : Facility for Antiproton and Ion Research, a proton, antiproton, and heavy ion accelerator at **GSI**.

FASER : Forward Search Experiment, designed to search for light, weakly interacting particles produced at the **LHC**.

FASERnu : An emulsion-based experiment to detector forward-produced neutrinos from the **LHC**.

FAST : Fermilab Accelerator Science and Technology facility, a accelerator research complex at **Fermilab**.

FCC : Future Circular Collider, a large circular collider project proposed for **CERN**.

FCC-ee : A large circular e^+e^- collider proposed as a phase of the **FCC** project.

FCC-hh : A large circular proton-proton collider proposed as a phase of the **FCC** project.

FCNC : Flavor-Changing Neutral Current.

FE : Front End.

FEL : Free Electron Laser, an electron accelerator that produces high-intensity coherent synchrotron radiation.

Fermi : Femtometer = 10^{-13}cm.

Fermi-GBM : Fermi Gamma-ray Burst Monitor, a space-based gamma-ray detector.

Fermi-LAT : Fermi Large Area Telescope, a space-based gamma-ray detector.

Fermion : A type of elementary particle whose intrinsic spin is a half-integer ($\frac{1}{2}$, $\frac{3}{2}$, ...) multiple of $\hbar$. Such particles can form rigid structures of matter such as atoms and atomic nuclei.

Fermilab : Fermi National Accelerator Laboration, in Batavia, Illinois.

FFA, FFAG : Fixed-Field Alternating Gradient accelerator, an accelerator based on time-independent magnetic fields and alternating gradient focusing.

FinFET : Fin-shaped Field Effect Transistor.

FLAG : Flavor Lattice Averaging Group, a collaboration of experts in lattice **QCD** and weak-interaction theory who evaluation and average results from the various lattice **QCD** collaborations.

fm : Femtometer or **Fermi** = 10^{-13}cm.

FNAL : Fermi National Accelerator Laboratory, or **Fermilab**.

FOA : Funding Opportunity Announcement.

Form Factor : A Lorentz-invariant function of kinematic variables characterizing an elementary particle scattering or decay process.

FoV : Field of View.

FPGA : Field-Programmable Gate Array, a programmable hardware device for very rapid computation.

FRIB : Facility for Rare Isotope Beams, a linear accelerator at Michigan State University for isotope production and nuclear structure research.

FrPNC : Francium Parity Non-Conservation, at experiment at **TRIUMF** to measure **P**-violating atomic transitions in francium atoms.

FSR : Final State Radiation, radiation from a lepton, quark, or gluon produced in a high-energy scattering process.

FTM : Fast Timing **MPGD**.

GaAs : Gallium Arsenide.

GALLEX : GALLium EXperiment, a radiochemical solar neutrino experiment located at **Gran Sasso**.

GammeV-CHASE : An experiment at **Fermilab** to search for **axions** using a laser beam in a strong magnetic field.

GAPS : General Antiparticle Spectrometer, an experiment to detect anti-matter, especially deuterons, produced by annihilating dark matter particles.

GARD : General Accelerator Research and Development program of the **DOE**.

GC : Galactic Center.

GDD : Gaseous Detector Development laboratory at **CERN**.

GDE : Global Design Effort, the collaboration responsible for the **ILC** Technical Design Report.

GE1/1, GE2/1 : **GEM** muon system stations in the **CMS** experiment

GEANT4 : A library of simulation programs describing the passage of high-energy particles through matter.

GEM : Gas Electron Multiplier, a type of **MPGD** ionization detector.

GEMMA : Germanium Experiment for measurement of the Magnetic Moment of Antineutrino, a neutrino magnetic moment experiment at the Kalinin nuclear power plant in Russia.

GERDA : Ge experiment searching for neutrinoless double beta decay.

GeV : Giga-electron Volt (10^9 eV), the energy scale of the proton mass and the subnuclear strong interactions.

GIM : Glashow-Iliopoulos-Maiani mechanism, a method for coupling quarks to the weak interactions that avoid flavor-changing **NC** processes, realized in the **SM**.

GLACIER : Giant Liquid Argon Charge Imaging Experiment, a proposed large liquid argon detector in Europe.

GNO : Gallium Neutrino Observatory, a radiochemical solar neutrino experiment at **Gran Sasso** (successor to **GALLEX**).

GPU : Graphics Processing Unit.

GR : General Relativity, Einstein's theory of gravity.

Gran Sasso : An Italian national laboratory under a mountain of the same name, about 120 km from Rome.

Grid : In computing, a network of distributed computer and storage resources. Typically, it refers to a network in which users need not know at which node the processor or data they are using resides.

GSI : Society for Heavy Ion Research (Gesellschaft für Schwerionenforschung), a nuclear physics research center in Darmstadt, Germany.

GUT : Grand Unified Theory, a unified theory of all microscopic particle interactions.

GW : Gravitational Wave.

GZK neutrinos : Greisen-Zatsepin-Kuzmin neutrinos, produced by ultra-high energy cosmic ray protons scattering off **CMB** photons.

HALO : Helium And Lead Observatory, lead-based supernova neutrino detector at **SNOLAB**.

HAWC : High-Altitude Water Cherenkov, a gamma-ray detector currently operating in Mexico.

HAYSTAC : Haloscope at Yale Sensitive To Axion CDM.

HE-LHC : High-Energy LHC, a proposed stage of the **LHC** in which the bending magnets are replaced by higher-field magnetics, to create *pp* collisions at center-of-mass energies of 26–33 TeV.

HEMT : High Electron Mobility Transistor.

H.E.S.S. : High Energy Stereoscopic System, a telescope for high-energy gamma rays seen as air showers in Cherenkov radiation, located in Namibia.

HEP : High-Energy Physics, the generic term for the areas of research described in this report.

HEPAP : High-Energy Physics Advisory Panel, a panel convened by the U.S. **DOE** and **NSF** to advise the federal government on high-energy physics research.

HERA : Hadron Elektron Ring Anlage, an electron-proton and positron-proton collider at **DESY** that operated from 1990 to 2007.

HETDEX : Hobby-Ebberly Telescope Dark Energy Experiment.

HFIR : High Flux Isotope Reactor, reactor facility at Oak Ridge National Laboratory.

HGCal : **CMS** High Granularity Calorimeter for **HL-LHC**.

HHCAL : Homogeneous Hadron Calorimeter, a concept for hadron calorimetry based on total absorption of hadrons in large crystals equipped with dual readout (see **DREAM**).

HIGS : High Intensity Gamma-ray Source, a free electron laser at Duke University.

HIKE : High Intensity Kaon Experiments, a proposed long-term, high-intensity experimental program at CERN to study rare K decays.

HiBM : High Intensity Muon Beam, a proposal at **PSI** for a high-intensity muon beamline.

HiRes : High Resolution Fly's Eye cosmic ray experiment in Utah.

HLbL : Hadronic Light-by-Light scattering contribution to the muon anomalous magnetic moment.

HL-LHC : High Luminosity LHC, the highest-luminosity phase of the **LHC**.

HNL : Heavy Neutral Lepton.

HPC : High Performance Computing, such as that done using supercomputers.

HPGArTPC : High pressure gaseous argon **TPC**.

HPQCD : High-Precision QCD, an international collaboration carrying out lattice **QCD** calculations.

HPS : Heavy Photon Search, an experiment at **JLab** searching for the decay of dark photons to e^+e^-.

HQE : Heavy Quark Expansion, a method for computing decay rates of heavy hadrons using **HQET**.

HQET : Heavy Quark Effective Theory, a method for computing properties of hadrons with a single c or b quark by expanding about the limit in which this quark is extremely heavy.

HSC : Hyper-Suprime Cam, wide-field camera for the Subaru telescope.

HSF : **HEP** Software Foundation

HTC : High Throughput Computing, i.e, data-intensive computing.

HTS : High-Temperature Superconductivity.

HVP : Hadronic Vacuum Polarization contribution to the muon anomalous magnetic moment.

Hyper-K : Hyper-Kamiokande, a proposed large water Cherenkov detector at Kamioka in Japan.

Hyperon : A baryon containing strange quarks.

IACT : imaging Atmospheric Cherenkov Telescope.

IAEA : International Atomic Energy Agency.

IAXO : International Axion Observatory.

IBD : Inverse Beta Decay, usually referring to the reaction $\overline{\nu}_e + p \to e^+ + n$.

IC : Integrated Circuit.

ICAL : Iron CALorimeter atmospheric neutrino experiment at **INO**.

ICARUS : Imaging Cosmic And Rare Underground Signals, a liquid argon neutrino detector originally located at **Gran Sasso** and now moved to the **SBN** beamline at **Fermilab**.

ICEBERG : Integrated Cryostat and Electronics Built for Experimental Research Goals, a **LAr** cryostate at **Fermilab**.

IceCube : A neutrino telescope located at the Amundsen–Scott South Pole station in Antarctica.

IceTray : A software framework developed and used by the IceCube experiment for both online and offline processing.

IDEA : Innovative Detector for an Electron-positron Accelerator.

IDS : International Design Study (for the Neutrino Factory).

IHEP : Institute of High Energy Physics of the Chinese Academy of Sciences, the major particle physics laboratory in China, located in Beijing.

ILC : International Linear Collider, an electron-positron linear collider with design **CM** energy 500 GeV.

ILD : International Linear collider Detector, a large detector proposed for **ILC** and **CLIC**.

InAs : Indium Arsenide.

Inclusive decay rate : Rate of particle decay to final states not fully specified by meeting a general description (for example, the "one-pion inclusive" decay rate).

InGrid : **MPGD** with integrated pixel readout.

Initial-state radiation : Radiation (in the form of photons or gluons) emitted by a primary particle in a collision process.

INO : India-based Neutrino Observatory, a future underground laboratory in Tamil Nadu, India.

I/O : Input/Output

IOPS : Input/output Operations Per Second.

IOTA : Integrable Optics Test Accelerator, an electron storage ring an electron and proton storage ring at **FAST** for beam dynamics research.

IP : Intellectual Property.

IPPOG : International Particle Physics Outreach Group, a network of science educators and communicators based at **CERN**.

IR : Infrared light.

ISIS : Research center at Rutherford Appleton Laboratory near Oxford.

IsoDAR : Isotope Decay At Rest experiment, a proposed cyclotron-based sterile neutrino experiment.

ISR : Initial State Radiation, radiation from a high-energy lepton, quark, or gluon emitted as it scatters from another high-energy particle.

JEF : JLab Eta Factory, an experiment at **JLab** for precision measurements of η and η' meson decays.

JLab : Thomas Jefferson National Accelerator Facility, in Newport News, Virginia.

J-PARC : Japan Proton Accelerator Research Complex, the laboratory hosting the major Japanese proton accelerator, located in Tokai.

JEM-EUSO : Extreme Universe Space Observatory onboard the Japanese Experiment Module, proposed ultra-high energy cosmic ray detector on the International Space Station.

JUNO : Jiangmen Underground Neutrino Observatory, a proposed large scintillator experiment for reactor neutrino oscillations located in China.

K2K : KEK to Kamioka, the first-generation long-baseline oscillation experiment using beam from **KEK** to **Super-K**.

KA25 : **DOE** funding stream for detector R&D and detector facilities.

KamLAND : Kamioka Liquid scintillator ANtineutrino Detector, a reactor neutrino experiment at Kamioka in Japan.

KamLAND-Zen : Zero neutrino double beta decay search, a neutrinolesss double beta decay experiment using a Xe-doped balloon deployed in **KamLAND**.

KATRIN : KArlsruhe TRItium Neutrino experiment, an experiment to measure neutrino mass from the endpoint of the tritium beta decay spectrum.

KEK : Ko-Enerugi Kenkyusho, the major high energy physics laboratory in Japan, located in Tsukuba.

KEKB : An e^+e^- collider operated at **KEK** from 1998 to 2010 in the center-of-mass energy region of 10 GeV. This collider is now upgraded to **SuperKEKB**.

KLOE, KLOE-2 : An experiment at **LNF** studying e^+e^- annihilation at energies near 1 GeV.

KM3NET : Multi-Km^3 Neutrino Telescope, a future deep-sea neutrino telescope in the Mediterranean sea.

KOTO : An experiment at **J-PARC** studying the rare decay $K_L^0 \to \pi^0\nu\overline{\nu}$.

kt : Kilotonne $= 10^6$ kilograms.

KID : Kinetic Inductance Detector.

ΛCDM : The standard model of cosmology in which the Universe consists of known particles, cold **Dark Matter** (CDM), and dark energy (Λ).

***L/E* :** Length (**baseline**) / Energy, a figure of merit for neutrino oscillation experiments.

LAGUNA : Large Apparatus studying Grand Unification and Neutrino Astrophysics, a collaborative project to assess the possibilities for a deep underground neutrino observatory in Europe; includes the **GLACIER** , **MEMPHYS**, and **LENA** concepts.

LANL : Los Alamos National Laboratory.

LANSCE : Los Alamos Neutron Science Center.

LAPPD : Large Area Picosecond Photo-Detectors project, a collaboration working to develop large-area flat-panel photon detectors.

LAr : Liquid argon.

LAr1 : A proposal to add additional liquid argon TPCs to the **Fermilab** Booster neutrino beamline.

LAr1-ND : A proposal to add a liquid argon TPC near detector in the **Fermilab** Booster neutrino beamline.

LArIAT : Liquid Argon In A Testbeam, a liquid argon TPC test beam experiment at **Fermilab**.

LARP : LHC Accelerator Research Program, a collaboration of U.S. national laboratories to develop technology for the current and future stages of the **LHC**.

LArPix : A low-power pixilated charge readout for an **LArTPC**.

LArTPC : Liquid Argon Time Projection Chamber.

LBNF : Long Baseline Neutrino Facility, comprising two installations, the LBNF Near Site at **Fermilab** and the LBNF Far Site at **SURF**, which together provide the beam, underground experimental halls, and infrastructure required to support **DUNE**.

LBNL : Lawrence Berkeley National Laboratory (formerly LBL, Lawrence Berkeley Laboratory).

LCF : Leadership Computing Facility, one of the **DOE**'s high-performance computing centers.

LDO : Low Dropout Regulators.

LEM : Large Electron Multipliers.

LENA : Low Energy Neutrino Astronomy, a proposed next-generation liquid scintillator detector.

LENS : Low Energy Neutrino Spectroscopy, a low-energy indium-based solar neutrino experiment.

LEP, LEP-2 : The Large Electron-Positron collider at **CERN**, which performed precision studies of the Z meson and searches for new phenomena from 1989 from 2000.

Lepton flavor universality : The feature of the **Standard Model** that the gauge forces act identically on the three types of charged leptons.

Leptonic decay : A particle decay with only leptons in the final state.

LGAD : Low Gain Avalanche Diode/Detector.

LHC : Large Hadron Collider, a large proton-proton collider at **CERN**, with design **CM** energy 14 TeV.

LHCb : An experiment at the Large Hadron Collider specialized to measure the production in the forward direction of hadrons containing heavy quarks.

LHeC : Large Hadron-electron Collider, a proposal for a high-energy electron beam colliding with the proton beam of the **LHC** at **CERN**.

LNF : Laboratori Nazionali di Frascati, the leading particle physics laboratory in Italy, located in Frascati, near Rome.

LO : Leading Order, applied to the level of a quantum field theory calculation (see also **NLO**).

LOI : Letter of Intent.

LPA : Laser Plasma Acceleration.

LRGs : Luminous Red Galaxies.

LSND : Liquid Scintillator Neutrino Detector, an experiment at Los Alamos National Laboratory searching for sterile neutrinos.

LSO : Lutetium Silicate (Lu_2SiO_5).

LSST : Legacy Survey of Space and Time (formerly, Large Synoptic Survey Telescope), now renamed the Vera Rubin Observatory.

LuSEE-Night : Lunar Surface Electromagnetics Experiment, Night phase.

LUX : Large Underground Xenon detector, a large **Dark Matter** detector using liquid Xenon.

LVD : Large Volume Detector, a neutrino observatory at **Gran Sasso** studying low-energy neutrinos from gravitational stellar collapse.

LXe : Liquid Xenon.

LYSO : Lutetium Yttrium OxyorthoSilicate ($Lu_2(1\text{-}x)Y_2(x)SiO_5$).

LZ : LUX-Zeplin, a current-generation xenon TPC **Dark Matter** detector.

MACS : Muonium-Antimuonium Conversion Spectrometer, an experiment at **PSI** searching for muonium-antimuonium conversion.

MADMAX : Magnetized Disc and Mirror Axion Experiment.

MAGIC : Major Atmospheric Gamma-ray Imaging Cherenkov telescope, a telescope for high-energy gamma rays seen as air showers in Cherenkov radiation, located in the Canary Islands.

MAJORANA : An experiment searching for neutrinoless double-beta decay in Ge, located at **SURF**.

MAMI : MAinzer MIcrotron, a low-energy electron accelerator at the University of Mainz.

Many-core : Refers to computer chips that contain many more cores than **multi-core CPU**s, i.e., more than than 16 **CPU**s.

MAPS : Monolithic Active Pixel Sensor.

MCP : Micro-Channel Plate.

ME0 : **GEM** muon system station in the **CMS** experiment.

MEG : MuEGamma experiment, an experiment at **PSI** searching for the decay $\mu \to e\gamma$. This experiment is now in its second phase, MEG-II.

MEMPHYS : MEgaton Mass PHYSics, a large water Cherenkov detector proposed for **CERN** or **ESS**.

MESA : Mainz Energy-Recovering Superconducting Accelerator, a proposed electron accelerator at the Universithy of Mainz.

MicroBooNE : Liquid argon TPC experiment in the Booster neutrino beamline at **Fermilab**.

MicroMegas : Micro-Mesh gas detector, a type of **MPGD** ionization detector.

Milagro : A water Cherenkov gamma-ray telescope located near **LANL**.

MILC : MIMD Lattice Computation, an international collaboration carrying out lattice **QCD** computations.

MINERνA : Main Injector Experiment for ν-A, a neutrino scattering experiment in the NuMI beamline at **Fermilab**.

MiniBooNE : A short-baseline neutrino oscillation experiment using a mineral oil-based Cherenkov detector in the Booster neutrino beamline at **Fermilab**.

MIND : Magnetised Iron Neutrino Detector, a proposed neutrino factory detector.

Minimal Flavor Violation : A scenario for models of new physics in which quark flavor is violated only by the **CKM** matrix, as in the **Standard Model**.

MINOS : Main Injector Neutrino Oscillation Search, a neutrino oscillation experiment located at **Soudan** using the NuMI beamline at **Fermilab**.

MIP : Minimum-Ionizing Particle.

MIT-LL : MIT Lincoln Laboratory.

MKID : Microwave Kinetic Inductance Detector.

ML : Machine Learning.

MNS : Maki-Nakagawa-Sakata matrix (see **PMNS**).

MOLLER : An experiment at **JLab** to measure the **P**-violating asymmetry in electron-electron scattering.

MOS : Metal Oxide Semiconductor, a class of semiconductor devices.

MOSFET : Metal Oxide Semiconductor Field Effect Transistor.

MOSIS : Metal Oxide Semiconductor Implementation Service.

MPGD : Micro-Pattern Gaseous Detector.

MPPC : Multi-Pixel Photon Counter.

$\overline{MS}$: Modified Minimal Subtraction, a prescription for removing divergences commonly used in high-precision quantum field theory calcuations.

MS-DESI : Mid-Scale Dark Energy Spectroscopic Instrument.

MSE : Maunakea Spectroscopic Explorer, a multi-object spectroscopy telescope on Mauna Kea.

MSSM : Minimal Supersymmetric Standard Model, the simplest (though, not very simple) model that extends the **SM** by the addition of **SUSY**.

MSW : Mikheyev-Smirnov-Wolfenstein effect, the modification of the neutrino oscillation probability as neutrinos pass through matter.

Multi-core : Refers to computer chips that contain up to about 16 **CPU**s.

Muon capture : Capture of a μ^- by a proton in an atomic nucleus, resulting in the reaction $\mu^- p \to n\nu_\mu$.

Muon $g-2$: An experiment at **Fermilab** to measure the anomalous magnetic moment of the muon.

Muonium : The bound state of a positive muon and a negative electron; antimuonium is the bound state of a negative muon and a positron.

Mu2e : An experiment at **Fermilab** searching for muon-to-electron conversion in the field of a heavy nucleus.

Mu3e : An experiment at **PSI** searching for the flavor-violating decay $\mu^+ \to e^+e^-e^+$.

mwe : Meters water-equivalent, a measure of the depth of an underground detector.

MWPC : Multi-Wire Proportional Chamber.

NA61/SHINE : **SPS** Heavy Ion and Neutrino Experiment, studying the hadronic final states produced in interactions of pion, proton, and berylium, argon, and xenon nuclei beam with a variety of fixed nuclear targets.

NA62 : An experiment at **CERN** measuring the rare kaon decay $K^+ \to \pi^+\nu\overline{\nu}$.

NASA : National Aeronautics and Space Administration.

NC : Neutral Current weak interactions.

ND-Gar : **DUNE** near detector made of gaseous argon.

nEDM : Neutron **EDM**.

NERSC : National Energy Research Scientific Computing Center.

NESSiE : Neutrino Experiment with SpectrometerS in Europe, a proposed experiment to search for sterile neutrinos using the **CERN** SPS beam and the **ICARUS** detector.

Neutrino mass ordering, or Neutrino mass hierarchy : The question of whether the neutrino mass eigenstate ν_3, with the smallest content of ν_e, has the heaviest or lightest of the neutrino masses. These two cases are called the "Normal hierarchy" and "Inverted hierarchy", respectively.

Neutino octants : Sectors of the parameter space of neutrino mixing in which the mixing angle θ_{23} is greater than or less than 45°. The region $\theta_{23} > 45°$ is also called the "dark side".

NEXT : Neutrino Experiment with Xenon TPC, a neutrinoless double beta decay experiment at the **Canfranc Underground Laboratory**.

NF : Neutrino Factory.

NIST : National Institute of Standards and Technology.

NLO, NNLO : Next-to-Leading Order, Next-to-Next-to-Leading Order, terms designating a quantum field theory calculation with two and three terms, respectively, in the power series in the coupling constant.

NLWCP : New, Light, Weakly-Coupled Particles.

NMR : Nuclear Magnetic Resonance.

NN : Neural Network.

NNbarX : An experiment proposed at **Fermilab** to search for neutron-antineutron oscillations.

NNSA : National Nuclear Security Administration.

NOMAD : Neutrino Oscillation MAgnetic Detector, a neutrino oscillation experiment at **CERN**.

Nonleptonic decay : A particle decay only hadrons in the final state.

NOνA : NuMI Off-Axis electron-neutrino Appearance experiment, a neutrino oscillation experiment in the **NuMI** beamline at **Fermilab**.

NP : Nuclear Physics.

NREN : National Research and Education Network, a high performance network designed for large scale data movement.

NSF : U.S. National Science Foundation.

NUFO : National User Facility Organization, the umbrella group for U.S. national user facility users' organizations.

NuMAX : Neutrinos from Muon Accelerators at Project X, a proposed neutrino oscillation experiment using a muon-storage ring as a source of neutrinos.

NuMI : Neutrinos at the Main Injector, a neutrino beamline at **Fermilab** using the Main Injector, extending to **Soudan** and Ash River, Minnesota.

nuSTORM : Neutrinos from STORed Muons, a proposed short-baseline neutrino experiment to study sterile neutrinos using a muon storage ring as a source of neutrinos.

NVRAM : Non-Volatile Random Access Memory.

OHEP : Office of High Energy Physics of the U.S. **DOE**.

OLCF : Oak Ridge Leadership Computing Center.

OPE : Operator Product Expansion, a method in Quantum Field Theory that approximates a product of operators at closely spaced points by a sum of local operators.

OPERA : Oscillation Project with Emulsion-tRacking Apparatus, an emulsion- and tracker-based neutrino oscillation experiment at **Gran Sasso**.

ORCA : Oscillation Research with Cosmics in the Abyss, a proposed experiment to measure the neutrino mass hierarchy using the **KM3NeT** neutrino telescope.

ORKA : A proposed **Fermilab** experiment to measure the rate of the decay $K^+ \to \pi^+ \nu\overline{\nu}$.

ORNL : Oak Ridge National Laboratory.

OscSNS : Oscillations at the Spallation Neutrino Source, a proposed sterile neutrino search using the SNS facility.

P : Parity, the inversion of all spatial coordinates.

PAMELA : Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics, space-based anti-matter detector.

PANDA : antiProton ANnihilation at Darmstadt, a proposed experiment at the GSI Helmholtzzentrum in Darmstadt, Germany, studying proton-antiproton annihilation at few-GeV energies.

PandaX : A liquid xenon **Dark Matter** experiment to be located in the Jin-Ping Underground Laboratory in Sichuan, China.

PB : PetaByte, equal to 10^{15} bytes of information.

PDC : Photon to Digital Converter.

PDF : Parton Distribution Function, a function that describes the internal structure of the proton by giving the momentum distribution of a particular constituent, for example, the up quark or gluon.

PEN : An experiment at **PSI** to measure the ratio of decay rates $\pi^+ \to e^+\nu$ / $\pi^+ \to \mu^+\nu$.

Persistency management : Management of persistent data on disk, tape, or other media. This includes reducing the risk of loss to an appropriate level.

PEP-II : An e^+e^- collider operated at **SLAC** from 1998 to 2008 in the center-of-mass energy region of 10 GeV.

PF : PetaFlop, 10^{15} floating point operations (usually, per second).

PF : Particle Flow.

PFA : Particle Flow Analysis/Algorithm, a method for hadron calorimetry based on separate measurement of the components of a hadronic shower with charged particles, photons, and neutral hadrons.

PFS : Prime Focus Spectrograph, wide-field multi-object spectrograph for the Subaru telescope.

PI : Principal Investigator.

Picosec : A fast timing **MPGD**.

PID : Particle Identification.

PIENU : An experiment at **TRIUMF** to measure the ratio of decay rates $\pi^+ \to e^+\nu$ / $\pi^+ \to \mu^+\nu$.

Pile-up : In collisions of a particle bunch with a fixed target or of two particle bunches in a colliding beam experiment, additional collision events superposed on the collision of primary interest. Pile-up is a major source of background events in high-intensity experiments.

PINGU : Precision IceCube Next Generation Upgrade, a proposed low-energy extension to **IceCube**.

PIONEER : An experiment at **PSI** to study lepton universality and CKM unitarity in rare pion decays.

PIP-II : Proton Improvement Plan II, a project to upgrade the Fermilab proton beam to 1.2 MW.

Pipeline computing : Data analysis that proceeds in stages.

PLL : Phase-Locked Loop.

pMSSM : phenomenological Minimal Supersymmetric Standard Model, a 19-parameter subspace of the full MSSM.

PMNS : Pontecorvo-Maki-Nakagawa-Sakata matrix, the matrix linking the mass and flavor eigenstates of neutrinos.

PMT : PhotoMultiplier Tube.

Port : To adjust and test a computer program to run on a new architecture, or the result of this process.

Portal : An interaction that connects particles in a **Dark Sector** with particles of the **Standard Model**.

PQ : Peccei-Quinn symmetry, an approximate symmetry of quark-Higgs boson interactions, which must also be spontaneously broken, that allows the possible **CP**-violating term in **QCD** to be set to zero. A consequence of this symmetry is the existence of the **axion**.

PRD : Primary Research Direction.

PREM : Preliminary Reference Earth Model, a model for the Earth's density distribution.

PREP : Physics Research Equipment Pool.

PRISM : Precision Reaction-Independent Spectrum Measurement, a technique to use measurements of neutrino beams at multiple off-axis angles to construct a data-driven prediction of the beam energy spectrum.

protoDUNE : Prototype detectors for **DUNE** operated in a test beam at **CERN**.

Project 8 : A proposed tritium-based neutrino mass experiment.

Project X : A planned upgrade of the proton accelerator injector complex at **Fermilab**, with a superconducting proton linear accelerator capable of producing multi-megawatt beams.

PROSPECT : Precision Reactor Neutrino Oscillation and Spectrum Experiment, a U.S.-based reactor short-baseline oscillation search experiment.

Protvino : The major particle physics laboratory in Russian, located in Protvino, Moscow region.

PSI : Paul Scherrer Institute, a national laboratory and accelerator center in Switzerland.

PTOLEMY : Princeton Tritium Observatory for Light Early-universe Massive neutrino Yield, a proposed relic Big Bang neutrino background experiment.

PUMA : Packed Ultrawideband Mapping Array.

PWFA : Plasma Wake Field Acceleration.

QC : Quantum Computer.

QCD : Quantum Chromodynamics, the well-established theory describing the strong subnuclear interactions.

QE : Quantum Efficiency.

QE : Quasi-Elastic scattering. In neutrino physics, a reaction such as $\nu n \to \mu^- p$ in which no mesons are produced. In other contexts, a quasi-elastic reaction on a nucleon can involve production of a low-lying nucleon resonance.

QED : Quantum ElectroDynamics.

QI : Quantum Information.

QIS : Quantum Information Science.

QPix : A pixilated readout technique for **LArTPC**s based on charge integration and reset (CIR) circuits.

Qweak : An experiment at **JLab** to measure Q_{weak}, the charge with which the proton couples to the Z boson at very low momentum transfer.

RADAR : R&D Argon Detector at Ash River, proposal to add a **LAr TPC** to the **NOνA** far detector building in Ash River, Minnesota.

Radiative decay : Particle decay with a photon in the final state.

RAT : A simulation and analysis package for optical detectors developed for the Braidwood project and now used within **SNO+**, **MiniClean**, and **DEAP**.

RAY : Rydberg Atoms at Yale.

RBC-UKQCD : RIKEN-BNL-Columbia-United Kingdom QCD, an international collaboration carrying out lattice **QCD** computations.

RD51 : **CERN** R&D collaboration for the development of MGPD technologies.

REAPR : Resonantly Enhance Axion Photon Regeneration, an experiment at **Fermilab** to search for **axions** using a laser beam in a strong magnetic field, the successor to **GammeV-CHASE**.

REDTOP : A proposed next-generation η and η' meson factory.

RENO : Reactor Experiment for Neutrino Oscillations, a reactor neutrino experiment in South Korea.

RENO-50 : A proposed reactor-based experiment with **baseline** ~ 50 km to measure the neutrino mass hierarchy with a large scintillator detector.

RF : Radio Frequency.

RFSoc : Radio Frequency System on Chip.

RHIC : Relativistic Heavy Ion Collider, a colliding beam acclerator for protons and heavy ions at **BNL**.

RIB : Rare Isotope Beam.

RICE : Radio Ice Cherenkov Experiment, neutrino detector in Antarctica.

RICOCHET : A proposed bolometric sterile neutrino search using **CENNS**.

RICH : Ring Imaging CHerenkov detector.

RIKEN : Rikaguka Kenkyujo, a major Japanese research institute covering physics, chemistry, and engineering, operating multiple research groups in Japan and one in the U.S. at **BNL**.

ROI : Region Of Interest. In neutrino physics, the region of a measured energy spectrum where the signal (typically a peak or dip from an oscillation) lies. In collider physics, a region of a detector whose data is used in trigger calculations.

RPC : Resistive Plate Chamber, a type of particle tracking detector.

RPWELL : Resistive-Plate Well Detector.

SAGE : Soviet American Gallium Experiment, a solar neutrino experiment in the **Baksan** Neutrino Observatory in Russia.

SBC : Scintillating Bubble Chamber, a proposed **DM** detector.

SBIR : Small Business Innovation Research, a grant category of the **DOE** for collaboration of small businesses with experimental projects.

SBN : Short Baseline Neutrino program at **Fermilab**.

SBND : Short Baseline Near Detector, a **LArTPC** detector in the **Fermilab SBN** program.

SCGSR : Science Graduate Student Research.

SciDAC : Scientific Discovery through Advanced Computation, a program of the **DOE**.

SCTF : Super Charm Tau Factory, a proposed e^+e^- collider at **BINP**.

Science DMZ : A portion of a computer network designed for high-performance scientific applications rather than general-purpose computing such as web browsing.

SciNOνA : A proposed neutrino scattering experiment adding a fine-grained scintillator detector at the **NOνA** near detector site.

SDSS : Sloan Digital Sky Survey, a survey of more than a quarter of the sky using the 2.5-meter telescope at Apache Point Observatory, New Mexico.

Secondary vertex : In a collision process, the location of the decay of a long-lived particle produced in the primary reaction.

Semileptonic decay : A particle decay with leptons plus one or more hadrons in the final state.

SiD : Silicon Detector, a detector with silicon tracking proposed for **ILC** and **CLIC**.

SiGe : Silicon Germanium.

SIMD : Single Instruction Multiple Data style of parallel programming.

SINDRUM-II : An experiment at **PSI** searching for muon-to-electron conversion in the field of Au atoms.

SiPM : Silicon PhotoMultiplier, a silicon-based photodetector operated in Geiger mode.

SKA : Square Kilometer Array radio telescope.

SLAC : SLAC National Accelerator Laboratory, originally named the Stanford Linear Accelerator Center, a U.S. national laboratory in Menlo Park, California.

SLC : SLAC Linear Collider, an electron-positron collider operated at **SLAC** from 1989 to 1998 to study the Z boson and develop the technology of linear colliders.

SM : Standard Model of particle physics, which describes the strong, electromagnetic, and weak interactions as mediated by vector fields.

SNO : Sudbury Neutrino Observatory, a solar neutrino experiment located in Sudbury, Ontario, Canada.

SNO+ : A successor to the **SNO** experiment aimed at the measurement of neutrinoless double-beta decay of tellurium.

SNOLAB : Underground science laboratory in the Vale Creighton Mine located near Sudbury, Ontario.

SNS : Spallation Neutron Source, at Oak Ridge National Laboratory.

SNSPD : Superconducting Nanowire Single Photon Detector.

SOI : Silicon on Insulator.

SOTA : State of the Art.

SOTP : State of the Practice.

Soudan : An underground laboratory in northern Minnesota, housing **MINOS** and low-background experiments.

SOX : A chromium and/or cesium source used with the **Borexino** detector to study the reactor neutrino anomaly.

SPAD : Single Photon Avalanche Detector.

Spec-S5 : Stage V Spectroscopic Facility

SpecTel : Spectroscopic Telescope, a proposed **Spec-S5** implementation.

SPS : Super Proton Synchotron at **CERN**.

SQuAD : Superconducting Qubit Advantage for **Dark Matter**.

SRAM : Static Random Access Memory.

srEDM : A proposed storage ring experiment to measure the proton's **EDM**.

SRF : Superconducting Radio Frequency (**RF**) cavities and associated technology.

SRS : Scalable Readout System.

STTR : Small business Technology TRansfer, a **DOE** program for this purpose.

STAR : Solenoidal Tracker at RHIC, a relativistic heavy ion collider experiment at Brookhaven.

STCF : Super Tau Charm Factor, a proposed e^+e^- collider at **IHEP** with a center of mass energy range of 2–7 GeV.

STEM : Science, Technology, Engineering, and Mathematics, typically describing a domain of education.

STEREO : Search for Sterile Neutrinos at ILL reactor, a reactor short-baseline oscillation search in France.

Subaru : An optical/infrared telescope on Mauna Kea operated by the National Observatory of Japan.

Super-K : Super-Kamiokande experiment, water Cherenkov detector in the Kamiokande mine in Japan studying proton decay as well as solar, atmospheric, and accelerator-produced neutrinos.

SuperKEKB : A high-luminosity electron-positron collider, with **CM** energy about 10 GeV, at **KEK**.

Super-NEMO : Super Neutrino Ettore Majorana Observatory, a neutrinoless double beta decay experiment in the Fréjus underground laboratory in France.

SURF : Sanford Underground Research Facility: An underground laboratory in the former Homestake Mine in Lead, South Dakota.

SUSY : SUperSYmmetry, a symmetry that links together **fermions** and **bosons**. In any realistic theory, supersymmetry requires a new space-time structure extending and generalizing that of relativity.

SWGO : Southern Wide-Field Gamma-Ray Observatory.

Theia : A proposed large-scale optical neutrino detector in which both Cherenkov and scintillation signals are used.

T : Time reversal, the transformation of reversing the direction of time.

T2K : Tokai to Kamiokande experiment, a neutrino oscillation experiment in Japan, using the **J-PARC** neutrino beam and the **Super-K** detector.

TA : Telescope Array, ultra-high-energy cosmic ray detector in Utah.

TCA : Telecommunications Computing Architechture.

TeV : Tera-electron Volt (10^{12} eV), the order-of-magnitude energy scale of Higgs boson physics.

TDAQ : Trigger and **DAQ**.

TDC : Time to Digital Converter.

TDR : Technical Design Report.

TES : Transition Edge Sensor, a cryogenic sensor based on the very small amount of energy needed to destroy superconductivity in a thin film painted on the surface of a detector.

Theta-QCD, θ_{QCD} : . The coefficient of an allowed **CP**-violating interaction in the Lagrangian of **QCD**.

THGEM : Thick **GEM** detector.

TKID : Thermally-mediated **KID**.

TLEP : Triple Large Electron-Positron collider, a proposed e^+e^- collider in a large circular tunnel, with **CM** energies from 90 to 350 GeV.

TPC : Time Projection Chamber, a type of particle detector in which ionization from a track flows to a wall of a detector and the arrival time and location are measured, producing a 3-dimensional image of the track.

TPU : Tensor Processing Unit.

TREK : Time Reversal Experiment with Kaons, an experiment at **J-PARC** to search for **T**-violating muon polarization in the decay $K^+ \to \pi^0 \mu^+ \nu$.

Trigger : Hardware and software decision process that determines which signals from an experiment will be recorded for further analysis.

Trigger bandwidth : The maximum rate of interactions in an experiment that can be accepted by the **trigger** and written to permanent storage.

TRIUMF : TRI-University Meson Facility, the national accelerator laboratory of Canada, located in Vancouver. It is now operated by a consortium of 15 universities.

TSV : Though-Silicon Via.

TWIST : TRIUMF Weak Interaction Symmetry Test, an experiment at **TRIUMF** measuring the decay distributions of polarized muons with high precision.

UCN : Ultra-cold neutrons.

UHE : Ultra High Energy, typically applied to cosmic rays with energies $> 10^{18}$ eV.

UQ : Uncertainty Quantification, in the context of **QIS**.

USQCD : A collaboration of U.S. scientists carrying out lattice **QCD** computations.

UV : Ultraviolet light.

VCSEL : Vertical Cavity Surface Emitting Laser.

VEPP : One of a series of electron-positron colliders at the Budker Institute of Nuclear Physics in Novosibirsk, Russia.

VERITAS : Very Energetic Radiation Imagine Telescope Array System, a telescope for high energy gamma rays seen as air showers in Cherenkov radiation, located in Arizona.

Vev : Vacuum expectation value, the value of a condensed field, such as the Higgs field, at every point in space.

Volunteer computing : A distributed computing effort in which computer resources are donated by the owner, for example, the SETI At Home project.

VUV : Vacuum ultraviolet light.

Wakefield : The electromagnetic field trailing a bunch of high-energy particles in an accelerating structure.

WATCHMAN : WATer CHerenkov Monitoring of Anti-Neutrinos, a collaboration of U.S.-based universities and laboratories conducting a site search for an advanced water Cherenkov demonstration detector.

WCTE : Water Cherenkov Test Experiment facility at **CERN**.

WDM : Wavelength Distribution Multiplexing.

WFIRST-AFTA : Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets

Wilson Coefficients : Coefficients of operators appearing in **OPE**s and **EFT**s, named after Kenneth G. Wilson.

WIMP : Weakly Interacting Massless Particle, a category of particle that might make up the **Dark Matter** of the universe.

WIPP : Waste Isolation Pilot Plant, an underground facility located in New Mexico.

Wire-Cell : Software package for signal processing and reconstruction in **LArTPC**s.

WLCG : Worldwide **LHC** Computing Grid.

XLZD : A proposed future Xenon-based **Dark Matter** detector.

YBCO : Yttrium Barium Copper Oxide, $YBa_2Cu_3O_{7-x}$, one of the first high-temperature superconductors.