- Final Scientific/Technical Report -

Theoretical Particle Physics in the Data-Driven Era

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Theoretical Particle Physics in the Data-Driven Era

Kyoungchul (K.C.) Kong

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1 Executive Summary

DOE award DE-SC0021447 supports theoretical research in high energy physics. PI and students are not a part of any experimental collaboration, even if some works were done in collaboration with experimental colleagues. All research products are in the form of research articles and they are publicly available under `inspirehep.net` and `arxiv.org`, which are typical publication methods in high energy physics. No invention or patent is involved with this research. No equipment or hardware is involved with the research under this award.

Research outcomes are used by colleagues in high energy physics, including both theorists and experimentalists. Therefore the outcome of research topics under this award supported the High Energy Physics experimental research program, both in understanding the data and in finding new directions for experimental exploration. The research materials are used to train undergraduate students, graduate students and postdoctoral scholars.

We summarize research activity under this award in the following section and major products are listed in section 3. Section 4 contains professional presentations given by PI. Other products developed during the award period are in section 5. Students' activities are summarized in section 6.

2 Summary of research activity

Theoretical research under this award includes several major parts to support experimental effort in energy frontier, intensity frontier and cosmic frontier. Collider studies and dark matter phenomenology are summarized in section 2.1 and section 2.2. PI's participation in the Snowmass community planning is summarized in section 2.3.

2.1 Collider Physics

Kinematic Variables and Feature Engineering for Particle Phenomenology: Kinematic variables have been playing an important role in collider phenomenology, as they expe- dite discoveries of new particles by separating signal events from unwanted background events and allow for measurements of particle properties such as masses, couplings, spins, etc. For the past 10 years, an enormous number of kinematic variables have been designed and proposed, primarily for the experiments at the Large Hadron Collider, allowing for a drastic reduction of high-dimensional experimental data to lower-dimensional observables, from which one can readily extract underlying features of phase space and develop better-optimized data-analysis strategies. We review these recent developments in the area of phase space kinematics, summarizing the new kinematic variables with important phenomenological implications and physics applications. We also review recently proposed analysis methods and techniques specifically designed to leverage the new kinematic vari- ables. As machine learning is nowadays percolating through many fields of particle physics including collider phenomenology, we discuss the interconnection and mutual complementarity of kinematic variables and machine learning techniques. We finally discuss how the utilization of kinematic vari- ables originally developed for colliders can be extended to other high-energy physics experiments including neutrino experiments.

Portraying Double Higgs at the Large Hadron Collider II: The Higgs potential is vital to understand the electroweak symmetry breaking mechanism, and probing the Higgs self-interaction is arguably one of the most important physics targets at current and upcoming collider experiments. In particular, the triple Higgs coupling may be accessible at the HL-LHC by combining results in multiple channels, which motivates to study all possible decay modes for the double Higgs production. In this paper, we revisit the double Higgs production at the HL-LHC in the final state with two b-tagged jets, two leptons and missing transverse momentum. We focus on the performance of various neural network architectures with different input features: low-level (four momenta), high-level (kinematic variables) and image-based. We find it possible to bring a modest increase in the signal sensitivity over existing results via careful optimization of machine learning algorithms making a full use of novel kinematic variables.

Resolving Combinatorial Ambiguities in Dilepton $t\bar{t}$ Event Topologies with Neural Networks: We study the potential of deep learning to resolve the combinatorial problem in SUSY-like events with two invisible particles at the LHC. As a concrete example, we focus on dileptonic $t\bar{t}$ events, where the combinatorial problem becomes an issue of binary classification: pairing the correct lepton with each b quark coming from the decays of the tops. We investigate the performance of a number of machine learning algorithms, including attention-based networks, which have been used for a similar problem in the fully-hadronic channel of $t\bar{t}$ production; and the Lorentz Boost Network, which is motivated by physics principles. We then consider the general case when the underlying mass spectrum is unknown, and hence no kinematic endpoint information is available. Compared against existing methods based on kinematic variables, we demonstrate that the efficiency for selecting the correct pairing is greatly improved by utilizing deep learning techniques.

Direct Higgs-top CP-phase measurement with $t\bar{t}h$ at the 14 TeV LHC and 100 TeV FCC: The study of the Higgs boson's properties is a cornerstone of the LHC and future collider programs. In this paper, we examine the potential to directly probe the Higgs-top interaction strength and CP-structure in the $t\bar{t}h$ channel with the Higgs boson decaying to bottom-quark pairs and top-quarks in the di-leptonic mode. We adopt the BDRS algorithm to tag the boosted Higgs and exploit the M_2-assisted reconstruction to compute observables sensitive to the CP-phase at the $t\bar{t}$ rest frame, where the new physics sensitivity can be enhanced. Performing a side-band analysis at the LHC to control the continuum $t\bar{t}b\bar{b}$ background, we find that the Higgs-top strength and CP-phase can be probed up to $\delta\kappa_t \lesssim 20\%$ and $|\alpha| \lesssim 36°$ at 95% CL, respectively. We also derive that a similar analysis at a 100 TeV future collider could further improve the precision to $\delta\kappa_t \lesssim 1\%$ and $|\alpha| \lesssim 1.5°$, where the CP-odd observables play a crucial role, boosting the sensitivity on the CP-phase.

Deep-Learned Event Variables for Collider Phenomenology: The choice of optimal event variables is crucial for achieving the maximal sensitivity of experimen- tal analyses. Over time, physicists have derived suitable kinematic variables for many typical event topologies in collider physics. Here we introduce a deep learning technique to design good event variables, which are sensitive over a wide range of values for the unknown model parameters. We demonstrate that the neural networks trained with our technique on some simple event topologies are able to reproduce standard event variables like invariant mass, transverse mass, and strans- verse mass. The method is automatable, completely general, and can be used to derive sensitive, previously unknown, event variables for other, more complex event topologies.

2.2 Dark Matter

Search Prospects for Axion-like Particles at Rare Nuclear Isotope Accelerator Facilities: We propose a novel experimental scheme, called DAMSA (Dump-produced Aboriginal Matter Searches at an Accelerator), for searching for dark-sector particles, using rare nuclear isotope ac- celerator facilities that provide high-flux proton beams to produce a large number of rare nuclear isotopes. The high-intensity nature of their beams enables the investigation of dark-sector particles, including axion-like particles (ALPs) and dark photons. By contrast, their typical beam energies are not large enough to produce the backgrounds such as neutrinos resulting from secondary charged particles. The detector of DAMSA is then placed immediate downstream of the proton beam dump to maximize the prompt decay signals of dark-sector particles, which are often challenging to probe in other beam-dump-type experiments featuring a longer baseline, at the expense of an enormous amount of the beam-related neutron (BRN) background. We demonstrate that BRN can be signifi- cantly suppressed if the signal accompanies multiple, correlated visible particles in the final state. As an example physics case, we consider ALPs interacting with the Standard Model photon and their diphoton decay signal at DAMSA implemented at a rare nuclear isotope facility similar to the Rare isotope Accelerator complex for ON-line experiment under construction in South Korea. We show that the close proximity of the detector to the ALP production dump makes it possible to probe a high-mass region of ALP parameter space that the existing experiments have never explored.

Implications of the XENON1T Excess on the Dark Matter Interpretation: The dark matter interpretation for a recent observation of excessive electron recoil events at the XENON1T detector seems challenging because its velocity is not large enough to give rise to recoiling electrons of O(keV). Fast-moving or boosted dark matter scenarios are receiving attention as a remedy for this issue, rendering the dark matter interpretation a possibility to explain the anomaly. We investigate various scenarios where such dark matter of spin 0 and 1/2 interacts with electrons via an exchange of vector, pseudo-scalar, or scalar mediators. We find parameter values not only to reproduce the excess but to be consistent with existing bounds. Our study suggests that the scales of mass and coupling parameters preferred by the excess can be mostly affected by the type of mediator, and that significantly boosted dark matter can explain the excess depending on the mediator type and its mass choice. The method proposed in this work is general, and hence readily applicable to the interpretation of observed data in the dark matter direct detection experiment.

2.3 Working group reports

Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics: A future Higgs Factory will provide improved precision on measurements of Higgs couplings beyond those obtained by the LHC, and will enable a broad range of investigations across the fields of fundamental physics, including the mechanism of electroweak symmetry breaking, the origin of the masses and mixing of fundamental particles, the predominance of matter over antimatter, and the nature of dark matter. Future colliders will measure Higgs couplings to a few per cent, giving a window to beyond the Standard Model (BSM) physics in the 1-10 TeV range. In addition, they will make precise measurements of the Higgs width, and characterize the Higgs self-coupling.

Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments: The search for CP violation in interactions of the Higgs boson with either fermions or bosons provides attractive reference measurements in the Particle Physics Community Planning Exercise (a.k.a. "Snowmass"). Benchmark measurements of CP violation provide a limited and well-defined set of parameters that could be tested at the proton, electron-positron, photon, and muon colliders, and compared to those achieved through study of virtual effects in electric dipole moment measurements. We review the current status of these CP-sensitive studies and provide projections to future measurements.

Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders: Constraining the Higgs boson properties is a cornerstone of the LHC program and future colliders. In this Snowmass contribution, we study the potential to directly probe the Higgs-top CP-structure via the $t\bar{t}h$ production at the HL-LHC, 100 TeV FCC and muon colliders. We find the limits on the CP phase (α) at 95% CL are $|\alpha| \lesssim 36^\circ$ with dileptonic $t\bar{t}(h \to b\bar{b})$ and $|\alpha| \lesssim 25^\circ$ with combined $t\bar{t}(h \to \gamma\gamma)$ at the HL-LHC. The 100 TeV FCC brings a significant improvement in sensitivity with $|\alpha| \lesssim 3^\circ$ for the dileptonic $t\bar{t}(h \to b\bar{b})$, due to the remarkable gain in the signal cross-section and the increased luminosity. At future muon colliders, we find that the bounds with semileptonic $t\bar{t}(h \to b\bar{b})\nu\bar{\nu}$ are $|\alpha| \lesssim 9^\circ$ for 10 TeV and $|\alpha| \lesssim 3^\circ$ for 30 TeV, respectively.

Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them: Intriguing signals with excesses over expected backgrounds have been observed in many astrophysical and terrestrial settings, which could potentially have a dark matter origin. Astrophysical excesses include the Galactic Center GeV gamma-ray excess detected by the Fermi Gamma-Ray Space Telescope, the AMS antiproton and positron excesses, and the 511 and 3.5 keV X-ray lines. Direct detection excesses include the DAMA/LIBRA annual modulation signal, the XENON1T excess, and low-threshold ex- cesses in solid state detectors. We discuss avenues to resolve these excesses, with actions the field can take over the next several years.

Muon Collider Physics Summary: The perspective of designing muon colliders with high energy and luminosity, which is being investigated by the International Muon Collider Collaboration, has triggered a growing interest in their physics reach. We present a concise summary of the muon collider potential to explore new physics, leveraging on the unique possibility of combining high available energy with very precise measurements.

The International Linear Collider: Report to Snowmass 2021: The International Linear Collider (ILC) is on the table now as a new global energy- frontier accelerator laboratory taking data in the 2030's. The ILC addresses key questions for our current understanding of particle physics. It is based on a proven accelerator technology. Its experiments will challenge the Standard Model of particle physics and will provide a new window to look beyond it. This document brings the story of the ILC up to date, emphasizing its strong physics motivation, its readiness for construction, and the opportunity it presents to the US and the global particle physics community.

3 Major Products Developed Under the Award

3.1 Publications in Refereed Journals

10. **Search Prospects for Axion-like Particles at Rare Nuclear Isotope Accelerator Facilities**, (with W. Jang, D. Kim, Y. Kwon, J. Park, M. Ryu, S. Shin, R. Van de Water, U. Yang, J. Yu), **submitted to Physical Review Letters**, arXiv:2207.02223 [hep-ph]

9. **Kinematic Variables and Feature Engineering for Particle Phenomenology**, (with R. Franceschini, D. Kim, K. Matchev, M. Park, P. Shyamsundar), **submitted to Review of Modern Physics**, arXiv:2206.13431 [hep-ph]

8. **Muon Collider Physics Summary** (with International Muon Collider Collaboration), Contribution to: 2022 Snowmass Summer Study, to be submitted to **submitted to European Journal of Physics C**, arXiv:2203.07256 [hep-ph]

7. **Portraying Double Higgs at the Large Hadron Collider II**, (with L. Huang, S. Kang, J. Kim, J. Pi), **JHEP 08 (2022) 114**, arXiv:2203.11951 [hep-ph]

6. **Resolving Combinatorial Ambiguities in Dilepton $t\bar{t}$ Event Topologies with Neural Networks**, (with H. Alhazmi, Z. Dong, L. Huang, J. Kim, D. Shih), **Phys. Rev. D 105 (2022) 11, 115011**, arXiv:2202.05849 [hep-ph]

5. **Direct Higgs-top CP-phase measurement with $t\bar{t}h$ at the 14 TeV LHC and 100 TeV FCC**, (with D. Gonçalves, J. Kim, Y. Wu), **JHEP 01 (2022) 158**, arXiv:2108.01083 [hep-ph]

4. **Deep-Learned Event Variables for Collider Phenomenology**, (with D. Kim, K. Matchev, M. Park, P. Shyamsundar), **submitted to Physical Review D**, arXiv:2105.10126 [hep-ph]

3. **Implications of the XENON1T Excess on the Dark Matter Interpretation**, (with H. Alhazmi, D. Kim, G. Mohlabeng, J. Park, S. Shin), **JHEP 05 (2021) 055**, arXiv:2006.16252 [hep-ph]

2. **Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2** (with LHC Reinterpretation Forum Collaboration), **SciPostPhys.9.2.022**, arXiv:2003.07868 [hep-ph], CERN-LPCC-2020-001, FERMILAB-FN-1098-CMS-T

1. **Higgs boson pair production at colliders: status and perspectives** (with J. Kim, K. Matchev, M. Park), **Review in Physics (2020) 100045**, **FERMILAB-CONF-19-468-E-T, LHCXSWG-2019-005**, arXiv:1910.00012 [hep-ph]

3.2 Working Group Reports, Proceedings, and Lecture Articles

5. **Report of the Topical Group on Higgs Physics for Snowmass 2021: The Case for Precision Higgs Physics** (with Higgs Working group), 2209.07510 [hep-ph]

4. **Snowmass White Paper: Prospects of CP-violation measurements with the Higgs boson at future experiments** (with A. Gritsan, R. Barman, I. Bozovic-Jelisavcic, J. Davis, W. Dekens, Y. Gao, D. Goncalves, L. Guerra, D. Jeans, S. Kyriacou, R. Pan, J. Roskes, N. Tran, N. Vukasinovic, M. Xiao), **Contribution to: 2022 Snowmass Summer Study**, 2205.07715 [hep-ex]

3. **Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders** (with R. Barman, M. Cassidy, Z. Dong, D. Goncalves, J. Kim, F. Kling, I. Lewis, Y. Wu, Y. Zhang, Y. Zheng), **Contribution to: 2022 Snowmass Summer Study**, arXiv:2203.08127 [hep-ph]

2. **Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them** (with Cosmic Frontier DM working group), **Contribution to: 2022 Snowmass Summer Study**, arXiv:2203.06859 [hep-ph]

1. **The International Linear Collider: Report to Snowmass 2021** (with Snowmass ILC working group), **Contribution to: 2022 Snowmass Summer Study**, 2203.07622 [physics.acc-ph]

4 Professional talks given by PI

4.1 Talks at conferences and workshops

6. *"Double Higgs Production at HL-LHC"*, Inha HTG workshop: Modern issues in Hadronic Physics (July 7-8, 2022), Inha University **(invited/plenary)**

5. *"Particle Physics in the Data-Driven/ML Era"*, Interplay of Fundamental Physics and Machine Learning, Aspen Center for Physics (June 30 - July 10, 2022) **(invited)**

4. *"Double Higgs Production at HL-LHC"*, 2022 Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M (May 24-27, 2022) **(invited/plenary)**

3. *"Double Higgs Production at HL-LHC"*, the tenth annual Large Hadron Collider Physics (LHCP2022) conference, May 16-20, 2022 **(invited, online)**

2. *"Double Higgs Production at HL-LHC"*, 2021 Chung-Ang University Beyond the Standard Model Workshop (February 1-3, 2021), Korea **(invited, online)**

1. *"New Fermions and Exotica"*, EF09: BSM: More general explorations (June 26, 2020), Snowmass, Energy Frontier **(invited overview talk, online)**

4.2 Seminars and colloquia talks

5. *"Double Higgs Production at HL-LHC"*, (July 26, 2022), Theory seminar, Center for Theoretical Physics of the Universe, Institute for Basic Science (remote seminar)

4. *"Double Higgs Production at HL-LHC"*, (June 16, 2022), Theory seminar, Brookhaven National Laboratory (remote seminar)

3. *"Resolving Combinatorial Ambiguities in Dilepton $t\bar{t}$ Event Topologies with Neural Networks"*, (March 10, 2022), seminar, Seoul National University of Science and Technology, Korea (remote seminar)

2. *"Particle Physics in Computing Frontier"*, (December 27, 2021), seminar, QUC Winter School on Energy Frontier "Synergy with the Computing Frontier" (online)

1. *"Particle Physics in Computing Frontier"*, (March 31, 2021), colloquium, Physics Department, Wichita State University (online)

4.3 Minor talks at KU

5. *"Theoretical Particle Physics in Computing Frontier"*, Graduate seminar at KU, 9/23/2022

4. *"Theoretical Particle Physics in Computing Frontier"*, Presentation in REU program, Physics and Astronomy, KU, 7/26/2022

3. *"Theoretical Particle Physics in Computing Frontier"*, Presentation in PHSX150, Seminar in Physics, Astronomy and Engineering Physics at KU, 11/5/2020

2. *"Theoretical Particle Physics in Computing Frontier"*, SPS Undergrad Research at KU, 11/2/2020

1. *"Theoretical Particle Physics in Computing Frontier"*, Graduate seminar at KU, 10/28/2020

5 Other Products Developed Under the Award

5.1 Other professional activities

Community Service

2022:	Organizing committee, ML/QML workshop, KIAS
2022:	Organizing committee, 4th Particle Physics on the Plains, KU
2022:	Organizing committee, AI in HEP (school), KIAS
2021 - 2022:	Member, Nominating Committee, APS Division of Particles and Fields
2019 - 2021:	General Secretary, Association of Korean Physicists in America (AKPA)
2021:	Physics textbook proposal review for American Institute of Physics
2021:	DOE grant reviewer
2021:	NSF grant reviewer

Referee : Journal of High Energy Physics, Physical Review D, Physical Review Letter, Physics Letters B, Review of Modern Physics, European Physical Journal C, Journal of Cosmology and Astroparticle Physics, Europhysics Letters, Journal of Physics G: Nuclear and Particle Physics, International Journal of Modern Physics A, SciPost, IEEE Transactions on Automation Science and Engineering

Invited Lectures at Schools

December 27-30, 2021 : KIAS QUC Winter School on Energy Frontier
"Synergy with the Computing Frontier"

Undergraduate Student Research

3 students	Fall 2022
2 students	Summer 2022
3 students	Spring 2022
3 students	Fall 2021
2 students	Summer 2021
6 students	Spring 2021
6 students	Fall 2020

5.2 Website or other Internet sites that reflect the results of this project

All publications (main research activity) are found in the web sites, `inspirehep.net` and `arxiv.org`, which are typical publication methods in high energy physics. Specifically, the following link include all publications `https://inspirehep.net/search?p=exactauthor%3AK.Kong.1+`.

5.3 Networks or collaborations fostered

Collaborators/coeditors during 11/01/2020 - 06/30/2022

Prof. H Alhazmi (Jazan University, Saudi Arabia), Prof. C. Arina (UCL, Belgium), Prof. R. Franceschini (INFN), Prof. D. Goncalves (Oklahoma State U), Dr. J. Hesig (UCL, Belgium), Dr. L. Hunag (Peking U, China), Dr. W. Jang (Texas Arlington), Dr. S. Kang (Sungkyunkwan U, Korea), Dr. D. Kim (Texas A&M), Dr. M. Kim (KIAS, Korea), Prof. Y. Kwon (Yonsei U, Korea), Prof. J. Kim (Chungbuk U, Korea), Prof. I. Lewis (Kansas), Prof. K. Matchev (University of Florida), Dr. G. Mohlabeng (BNL), Dr. S. Mrenna (Fermilab), Prof. J. Park (Chungbuk U, Korea), Prof. M. Park (Seoul Tech. U., Korea), Dr. M. Ryu (Kyungbuk U, Korea), Prof. D. Shih (Rutgers), Dr. S. Shin (Chonnam U, Korea), Dr. P. Shyamsundar (Fermilab), Prof. U. Yang (Seoul U, Korea), Prof. J. Yu (Texas Arlington), Prof. Y. Wu (Oklahoma State U), Dr. Y. Zheng (Iwate U, Japan)

5.4 Inventions/Patent Applications, licensing agreements

None available.

6 Summary of Students Activities

DOE supported travels for PI, postdocs and students.

Talks given by a current PhD student, A

Machine-Learning quantum entanglement with top quark pair production at the LHC, PPC2022
Machine-Learning quantum entanglement with top quark pair production at the LHC, Pheno22
Revisiting the dileptonic $t\bar{t}$ combinatorial problem with machine learning, APS Prairie
Resolving the dileptonic $t\bar{t}$ combinatorial problem, Pheno2021

Schools attended by a current PhD student, A

CODAS-HEP 2022,	August 1-5, 2022, Princeton
2022 CTEQ school,	July 6 - July 16, 2022, Pittsburgh
7th Machine Learning in High Energy Physics Summer School,	July 15 - July 30, 2021, online
ICTP summer school,	May 31 - June 11, 2021, online

Talks given by a former PhD student, B

Seminar at Jeonbuk National University, July 7, 2021,
"Charting the Unknowns: the Hunt for Dark Matter Continues",

Graduate Students Advising at the University of Kansas

E	current, PhD expected in 2027
D	current, PhD expected in 2026
C	current, PhD expected in 2025
B	PhD 2021 → assistant professor at Jazan University, Saudi Arabia
A	PhD 2017 → BNL → Queens University, Canada → UC Irvine, will join as a junior faculty at Simon Fraser University, Canada