Final Report for DOE Early Career # DE-SC0015973

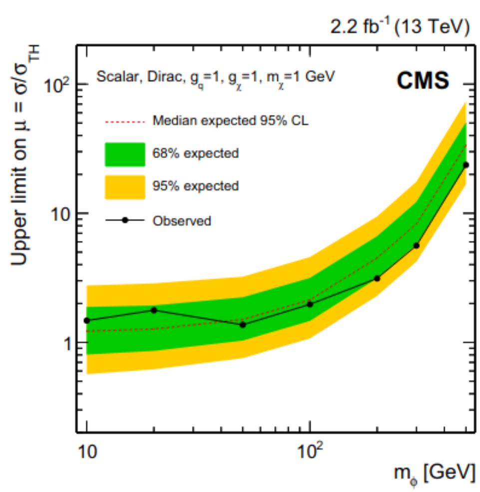
Principal Investigator: **Kristian Hahn**

This report summarizes the progress from DOE Early Career Award entitled "**Dark Matter and Track Triggering with the CMS Experiment**". The first major goal of the project was to establish a sensitive Dark Matter (DM) search program for the CMS experiment in Run-2 of the LHC. Two related strategies were developed to accomplish this goal. First, we designed and executed searches for DM produced in association with heavy flavor quark pairs, top/anti-top (ttbar) and bottom/anti-bottom (bbbar). In addition, we sought to maximize the power of Run-2 DM searches through the development of a statistical combination of all major search channels within a consistent theoretical framework. The results of these aspects of the project are detailed in Section 1.

The second major goal of the project was to develop a real-time "Level-1" tracking trigger system for the high-luminosity LHC (HL-LHC) CMS upgrade. Charged particle tracking in the first stage of the CMS trigger will be crucial for surviving the high-pileup environment expected at the HL-LHC. The L1 tracking trigger must process all front-end hit data sent from the inner Tracker and will have just 4us to output track primitives to the downstream L1 trigger without data loss. Our development of the CMS tracking trigger is described in Section 2.

The team supported by the award is given in Section 3. The project resulted in 10 peer reviewed publications, a graduate student thesis, and contributions to the CMS Phase-2 Tracker Technical Design Report, as is detailed in Section 4. Our development work for the CMS tracking trigger has been integrated in the backend system architecture for the Tracker upgrade.

1 Dark Matter Searches with CMS

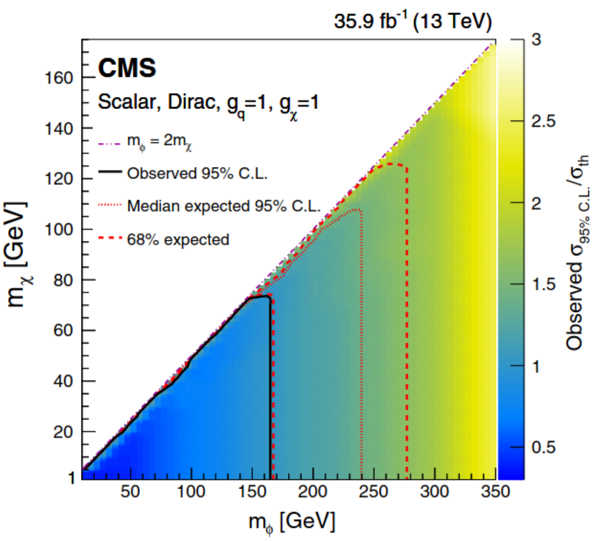


Figure–1: Upper limits on the combined tt + $\chi\chi$ and bb+$\chi\chi$ cross section to simplified model expectations.

The Run-1 CMS ttbar+DM search focused only on the semileptonic top decay channel, and results were interpreted using an Effective Field Theory of DM production model. Our first task was to development a ttbar + DM search for Run-2 of the LHC that included each of the ttbar decay modes. To maximize the sensitivity of the search in the all-hadronic channel, we developed a "resolved top tagging" discriminant to identify the decays of top quarks into three jets. We showed that by categorizing hadronic channel events in the number of resolved top tags, sensitivity improved by $> 40\%$.

We interpreted search results using a simplified model of ttbar+DM production that we had developed in the ATLAS/CMS Dark Matter Forum (DMF). We completed the analysis of the hadronic, semileptonic, an all-leptonic ttbar + DM channels on 2.2 fb-1. This work also combined ttbar + DM results with the bbbar + DM channel, providing the first consistent search for spin-0 DM mediators produced in association with heavy flavor. Results from this analysis were presented at ICHEP'16, DM@LHC, Moriond 2017 and the 2017 Aspen Winter Conference and published in EPJC C77 (2017) 845. The limits set in this search (*e.g.* Figure-1) were the world's strongest for a period.

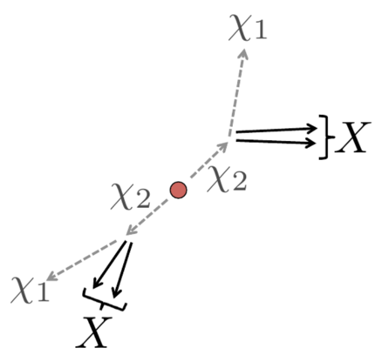
In 2017 and 2018 we focused on running the ttbar+DM search with the 36 fb-1 Run-2 dataset. Because of the larger (by a factor of 15) datasets and re-optimizations to the analysis, our 36 fb-1 search dramatically improved limits on ttbar+DM production. For the first time, a ttbar+DM search excluded mediator masses below the top threshold for the nominal DM-mediator coupling of 1.0 (see Figure-2). Our results provided the most stringent limits to date on scalar-mediated Dark Matter production, and are the most constraining for low-mass pseudoscalar mediators. The search was published in PRL 122 011803 (2019). The 36 fb-1 search in the ttbar dileptonic channel was the focus of graduate student Stanislava Sevova's thesis. In the same period we also contributed to the development of a novel analysis that incorporates Dark Matter production via the single-top channel. This search was developed in 2018 and published in JHEP 03 (2019) 141.



Figure–2: Exclusion limits at 95% C.L. on the signal strength μ computed as a function of the mediator and dark matter mass.

Our other DM-related accomplishments include activities that supported the development of the ttbar+DM search, or that connected more generally to the comprehensive DM search program in CMS. First, we contributed to the development of a new spin-0 simplified model that can be used as a basis for the consistent combination of all applicable CMS DM search channels. The spin-0 simplified models developed in the DMF do not account for mixing between the DM mediator and the SM Higgs. The lack of scalar mixing can lead to a misleading picture of the sensitivity of various search channels. The "Scalar Model with Mixing" (SMM) we developed in whitepaper arxiv:1607.06680 addresses this shortcoming. In 2017, we participated in the development of new Two-Higgs doublet simplified models for DM production at the LHC as part of the LHCC Dark Matter Working Group. This work connected with other efforts we undertook with the DMWG to structure DM searches at the LHC. Many of the whitepapers produced by the DMWG were later published in *Physics of the Dark Universe*.

Finally, we developed methodologies and models that extend the standard DM simplified models with long-lived signatures. Theories that provide DM candidates frequently also involve long-lived phenomena, which typically manifest as displaced signatures in the detector. One approach for confronting such possibilities is to consider slightly less-simplified models that contain multiple mediator and DM species. In these multi-component DM simplified models, the coupling of DM to standard model particles can be much weaker than what the canonical WIMP model would imply. The feeble couplings and potentially small mass splittings of these models can give rise to experimental signatures that involve displaced decays and suppressed $\not\!\!E_T$ signatures, as shown in Figure 3. Such signatures could be easily overlooked by the trigger selections and offline reconstruction algorithms used in present-day DM searches. In JHEP 9 (2017) 076, we showed how existing simplified models can be extended to include these signatures, and probe a wider variety of DM physics. A DM search inspired by our extended simplified models is presently underway in CMS.



Figure–3: The production of DM particles (χ_1) and displaced vertices from visible particles (X) from a long-lived mediator (χ_2).

During the award period, Hahn's group contributed to the broader DM search efforts of CMS and the LHC community. Hahn and postdoc Kevin Sung were the primary editors of the EPJC and PRL articles, respectively. Both Hahn and Sung were involved in CMS Analysis Review Committees for CMS DM searches. Hahn served as co-chair of the LPCC DMWG until 2018.

2 Hardware Tracking & the Tracker Back-end Electronics Upgrade

The second focus of the project was the development of hardware track triggering capabilities for the High-Luminosity upgrade of the CMS Tracker. Triggering is a necessity at the LHC. The vast majority of LHC collisions produce physics that is well understood and therefore uninteresting in the context of new physics searches. To provide statistically significant yields for rare new physics signals, the LHC must collide proton bunches at high frequency, resulting in an enormous rate of raw data from the CMS detector that is dominated by unremarkable physics. The task of the L1 trigger is to reduce this rate by selecting only interesting, signal-like collisions from the pervasive and background in real-time.

This task will become significantly more difficult at the HL-LHC. Estimates for the average number of inelastic *pp* interactions occurring in each HL-LHC beam crossing range from 140 to 200. Debris from these "pile-up" collisions can mimic or degrade the detector signatures of any new or interesting physics process. For CMS to realize the unprecedented sensitivity to new physics promised by the HL-LHC upgrade, the experiment must first minimize the impact of pile-up interactions on L1 trigger performance. Charged particle tracking provides a most effective means of pileup mitigation, and track triggering capabilities are central to the design of the next-generation CMS Tracker detector.

Our accomplishments for the L1 tracking aspect of the project included the technical demonstration of an associative memory (AM)+FPGA approach. We completed the development of data delivery firmware for the AM+FPGA system in the autumn of 2016. This firmware enabled the receipt of front-end module on the ATCA motherboards that host the AMs ASICs and FPGAs. The firmware implements data sharing among the ATCA boards by means of the ATCA backplane and enables time-multiplexing by directing data flow to a single mezzanine card of an individual motherboard for a given BX. We designed the system using an efficient 64b/66b protocol capable of running at 10 Gbps. We demonstrated our data delivery system as part of the CMS Tracker project review that was held in December 2016 at CERN. As part of the demonstration, we succeeded in limiting the latency from data delivery to $< 1.2\ \mu s$, which was significantly less that what had been originally budgeted for. Much of our work on the AM+FPGA system is documented in a recent *JINST* publication.

Following a project review in 2017, CMS took a decision to pursue an all-FPGA solution for L1 tracking. Subsequently, we transitioned our developments to the newly established all-FPGA project, focusing initially on the implementation of L1 tracking using High Level Synthesis (HLS). HLS allows algorithm firmware to be implemented in languages such as C or C++, potentially eliminating the need to code with HDL languages. As such, HLS can broaden the project's development base, provide shorter development cycles, and improve long-term firmware maintainability. We contributed to several studies showing how HLS can be used, and the project has now adopted HLS as a baseline. We developed a first HLS prototype of one element (the so-called "Tracklet Engine") of the L1 tracking chain, which we are using to refine performance and resource utilization estimates for the project.

The main focus of our work for the L1 tracking project instead involved the development of low-level firmware for the CMS *Apollo* track finder boards. This effort included:

- The implementation of a common infrastructure firmware framework (EMP) that will be used across the Tracker backend systems in Phase-2. The use of a common framework will allow users to focus on the development of application specific functionalities (eg: the tracking algorithm) while the low-level operations associated with high-speed data links, timing and synchronization, buffer management, etc. are handled by the infrastructure. The adoption of EMP across the Tracker will ensure compatibility between the various Tracker hardware platforms and reduce support needs for the upgrade project.

- Our implementation of EMP allowed my group to perform the first 25 Gbps board-to-board data transfer tests between a "Serenity" blade (a prototype for the Outer Tracker DTC) and the Apollo. This demonstration made use 24 64b/66b data links between the two boards and required us to implement synchronization to the LHC clock.

- The continued development of L1 tracking HLS and implemented a first algorithm chain within EMP ans a processing payload. With this implementation we performed the first hardware demonstration of a portion of the hybrid tracking algorithm. To support this testing, we extended the EMP infrastructure to provide wider fan-in/fan-out capabilities, which are needed for performing scaling tests of the algorithm.

- The completion of a first implementation of the "SlinkRocket"protocol on the Apollo, which will be used for data transfer to central DAQ upon L1 accept. The team first worked on Slink integration and wrote an interface module to bridge data from the EMP framework to the SlinkRocket cores distributed by CERN. A block diagram of the interface module is shown in Fig. **??**. Data flow nominally originates from the EMP "payload", which in the case of the TF is the hardware tracking algorithm. The interface provides an ability to inject/capture data at several points within the stream to aid in debugging. Using this interface, Hahn's team was the first in CMS to demonstrate SlinkRocket communication between subsystem boards and the DTH. The group's EMP/slink interface is actively used by Tracker backend developers now and was ultimately merged into the main EMP development repository soon for use also in the CMS HGC, BRIL, MTD and L1 projects.

- Interfacing the Tracker backend systems with the DTH's timing and control distribution system (TCDS). The DTH distributes a high-precision 320 MHz clock, the 40 MHz LHC clock, and control/status signals over the ATCA backplane to CMS subsystem backends. Several hardware incompatibilities with the design of TCDS system became apparent while integrating TCDS in EMP with prototype Apollo hardware. These incompatibilities are related to the configuration of the transceivers used for TCDS communication on the Tracker boards and will be addressed in future revisions of the Tracker hardware. To proceed in the interim, Hahn's team proposed to reroute TCDS signals from the backplane to optical transceivers, allowing for TCDS communication between the DTH and Tracker boards to be tested via fibre.

These developments were crucial steps in the evolution of the L1 tracking project; not only did they provide capabilities required for the project, but also allowed for a clear understanding the resource constraints for the FPGAs on which they will be implemented. Figure-4 shows the ATCA shelf at the CERN TIF that Hahn's team used extensively for their development work.

Hahn served as co-convener of the CMS L1 Tracking Working Group until 2017 and co-authored the sections of the CMS Tracker Technical Design Report (TDR) that pertain to L1 tracking. Hahn served as co-convener the later CMS Tracker Upgrade Data Processing Systems (DPS) Group from 2017-2020. The DPS Group is responsible for overseeing the design, production, and integration of the Outer Tracker (OT) and Inner Tracker (IT) DTC boards and the L1 Track Finder. As co-convener, Hahn led the group in establishing a system specification for the Tracker backend electronics. The specification clarifies the roles of the Apollo and Serenity boards in the back-end system, details the 25 Gbps data links used for stub transfer between the OT DTC and TF, and describes the Tracker interfaces to central CMS DAQ. Crucially, the specification also establishes a baseline L1 tracking algorithm as a combination of Tracklet pattern recognition and a Kalman filter track fitter, thus harmonizing algorithm development efforts within the Tracker project.

Figure–4: An ATCA shelf at the CERN TIF containing Apollo, Serenity, and DTH boards. Hahn's team has established multi-gigabit communication between each of the boards in this crate.

3 Personnel

The award supported the work of all members of Hahn's team during the project period. The team included :

- **PI:** Kristian Hahn
- **Postdocs:** Kevin Sung, Marco Trovato (partial)
- **Graduate Students:** Stanislava Sevova, Yihan Liu (partial)

4 Summary of Publication Products

1. **CMS** Collaboration, A.M Sirunyan A.M. et al., "Search for dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J.* **C 77** 845 (2017). [https://doi.org/10.1140/epjc/s10052-017-5317-4]

2. A, Albert et al., "Towards the next generation of simplified Dark Matter models", arXiv:1607.06680, [https://doi.org/10.48550/arXiv.1607.06680]

3. **CMS** Collaboration, A.M Sirunyan A.M. et al., "Search for Dark Matter Particles Produced in Association with a Top Quark Pair at $\sqrt{s} = 13$ TeV", *Phys. Rev. Lett.* **122** 011803 (2019). [https://doi.org/10.1103/PhysRevLett.122.011803]

4. O. Buchmueller et al, "Simplified models for displaced dark matter signatures", *J. High Energ. Phys.* **76** (2017). [https://doi.org/10.1007/JHEP09(2017)076]

5. K. Klein et al, "The Phase-2 Upgrade of the CMS Tracker", CERN-LHCC-2017-009, CMS-TDR-014, CERN-LHCC-2017-009, CMS-TDR-014 (2017). [10.17181/CERN.QZ28.FLHW]

6. Stanislava Sevova, "A Search for Dark Matter Produced in Association with a Top Quark Pair at $\sqrt{s} = 13$ TeV in the Dilepton Final State with the CMS Detector", Northwestern University Dissertation (2018). [https://doi.org/10.21985/n2-83x9-vq61]

7. **CMS** Collaboration, A.M Sirunyan A.M. et al., "Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV", *J. High Energ. Phys.* **141** (2019). [https://doi.org/10.1007/JHEP03(2019)141]

8. A. Albert et al., "Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for dark matter mediators in visible and invisible decay channels and calculations of the thermal relic density", *Phys. Dark Univ.* **26** 100377 (2019).

   [https://doi.org/10.1016/j.dark.2019.100377]

9. A. Boveia et al., "Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter", *Phys. Dark Univ.* **27** 100365 (2020). [https://doi.org/10.1016/j.dark.2019.100365]

10. T. Abe et al., "LHC Dark Matter Working Group: Next-generation spin-0 dark matter models", *Phys. Dark Univ.* **27** 100351 (2020). [https://doi.org/10.1016/j.dark.2019.100351]

11. E. Batrz et al., "FPGA-based tracking for the CMS Level-1 trigger using the tracklet algorithm", *JINST.* **15** P06024 (2020). [10.1088/1748-0221/15/06/P06024]

12. S. Ajuha et al., "Charged particle tracking in real-time using a full-mesh data delivery architecture and associative memory techniques", *JINST.* **17** P12002 (2022). [10.1088/1748-0221/17/12/P12002]