Final Technical Report for

"Paths to Discovery at the LHC: Dark Matter and Track Triggering"

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10/24/16

DOE Award Number:	DE-SC0014073
Recipient/Institution:	Kristian Hahn, Northwestern University
Address:	2145 Sheridan Rd.
	Evanston IL, 60208
	Tech F115
Lead PI Information:	Kristian Hahn
	(847) 467-8847
	kristian.hahn@northwestern.edu
Administrative Contact:	Elizabeth Adams
	(847) 491-4800
	OSR-Evanston@northwestern.edu
FOA Number:	DE-FOA-0001140
Program Office:	Office of High Energy Physics
Technical Contact:	Abid Patwa
Research Area:	Experimental Research at the Energy Frontier

Introduction

Particle Dark Matter (DM) is perhaps the most compelling and experimentally well-motivated new physics scenario anticipated at the Large Hadron Collider (LHC). The DE-SC0014073 award allowed the PI to define and pursue a path to the discovery of Dark Matter in Run-2 of the LHC with the Compact Muon Solenoid (CMS) experiment. CMS can probe regions of Dark Matter phase-space that direct and indirect detection experiments are unable to constrain. The PI's team initiated the exploration of these regions, searching specifically for the associated production of Dark Matter with top quarks. The effort focuses on the high-yield, hadronic decays of W bosons produced in top decay, which provides the highest sensitivity to DM produced via through low-mass spin-0 mediators. The group developed identification algorithms that achieve high efficiency and purity in the selection of hadronic top decays, and analysis techniques that provide powerful signal discrimination in Run-2.

The ultimate reach of new physics searches with CMS will be established at the high-luminosity LHC (HL-LHC). To fully realize the sensitivity the HL-LHC promises, CMS must minimize the impact of soft, inelastic ("pileup") interactions on the real-time "trigger" system the experiment uses for data refinement. Charged particle trajectory information ("tracking") will be essential for pileup mitigation at the HL-LHC. The award allowed the PI's team to develop firmware-based data delivery and track fitting algorithms for an unprecedented, real-time tracking trigger to sustain the experiment's sensitivity to new physics in the next decade.

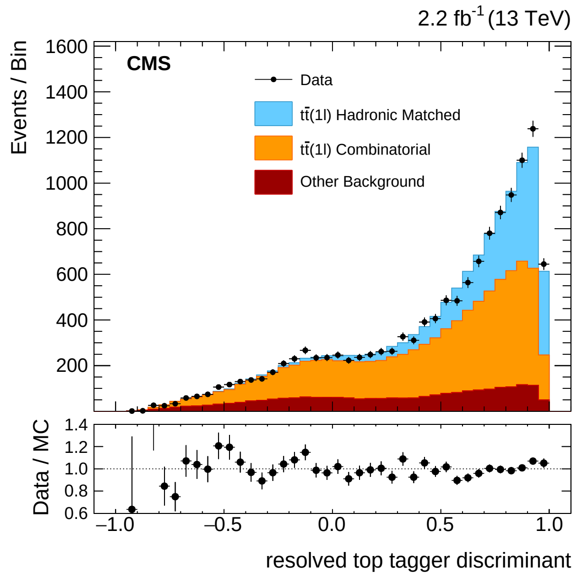
Timelines, Group & Goals

The PI's original proposal spanned 2015-2017. In this period, the PI anticipated analyzing the first Run-2 data in CMS, developing an optimized DM search for ~ 30 fb^{-1}, and implementing a hardware-based tracking trigger demonstration system. The DE-SC0014073 award cover 6/15-3/16 only, as the PI was expected to join the Northwestern University HEP umbrella grant.

The primary goals for the DM search in the 2015-2016 period included the development and characterization of a novel resolved top-tagger, and the utilization of the shape of the missing transverse energy ($\not{E}_T$) distribution for signal extraction. The main goals for the tracking trigger in this period were to complete the development of the data delivery system, and to implement a prototype tracking algorithm in hardware. To support this work, the PI requested a stipend for his graduate student, Stanislava ("Stany") Sevova, and salary support for his postdoc, Kevin Sung. Kevin has been based at CERN since his hire in 2013. Stany has been permanently based at CERN starting in the summer of 2015. During this period, Northwestern postdoc Marco Trovato officially joined the PI's group (supported though start-up), with an interest in contributing to the hadronic $t\bar{t}+$ DM channel and implementing the hardware-based track fit. The increase in person-power allowed the team to expand their analysis efforts into the semileptonic and dileptonic $t\bar{t}+$ DM search channels.

Dark Matter Search

The $t\bar{t}+\not{E}_T$ search will be primarily sensitive to DM scenarios with low-mass mediators for most of Run-2. Such scenarios produce $t\bar{t}$ final states in which top decay products are only moderately boosted. For this reason, the team focused on developing a novel resolved tagger in 2015 for application in the hadronic search channels. This multivariate discriminant utilizes properties of resolved top decay kinematics and jet observables, and presently includes quark/gluon likelihoods, b-tagging discriminants and a likelihood derived from a kinematic fit of jet triplets to the top and W masses. Figure-1 shows the discriminant distribution in a sample enriched in $t\bar{t}$. The plot shows good separation between the semileptonic $t\bar{t}$ signal and the combinatorial/dileptonic background. Sevova presented the group's resolved top tagging results at BOOST 2016 [1].

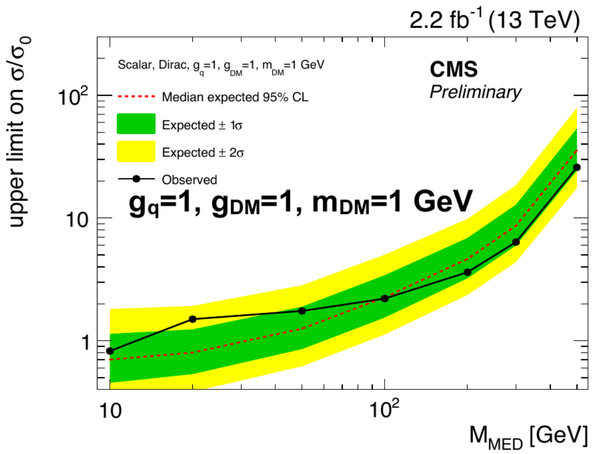


Figure–1: The distribution of the resolved top tagger discriminant in semileptonic $t\bar{t}$ events. Simulated semileptonic $t\bar{t}$ events in which jets from the hadronic top decay are correctly chosen are labeled "$t\bar{t}(1\ell)$ Hadronic Matched". Semileptonic $t\bar{t}$ events in which an incorrect combination of jets are chosen are labeled "$t\bar{t}(1\ell)$ Combinatorial". Events from processes that do not contain a hadronically decaying top quark (primarily, dileptonic $t\bar{t}$) are labeled "Other Background". Uncertainties on the ratio of data to simulation are statistical.

The team used the tagger to develop high-purity signal regions for a categorized $t\bar{t} + \not\!\!E_T$ search in the hadronic channel. Later in 2015-2016, the group also developed semileptonic and dileptonic channel searches. These efforts have since culminated in the first combined search results for $t\bar{t}+$ DM in the hadronic and semileptonic channels [2] (Figure-2a, shown at ICHEP 2016 [3]) and the first CMS Run-2 search results in the dileptonic channel [4] (Figure-2b). The PI presently serves as editor for the publication of combined search results for DM produced in association with heavy flavor quarks, which includes all $t\bar{t}$ channels, together with $b\bar{b}$.

L1 Tracking Trigger

The PI collaborates closely with a team at Fermilab on the development and prototyping of technologies for the CMS L1 tracking trigger. The effort enables L1 tracking through massively parallel computation. Chip-level parallelism is achieved with content addressable associative memories (AMs) for the pattern recognition task. The PI's team was the first university group to join the U.S. AM project, and is deeply involved in many aspects of its development. Much of the team's effort has focused on the implementation of a capable and flexible data distribution system for L1 tracking. The system must provide sufficient bandwidth for stub transfer, minimal link latency and



(a)

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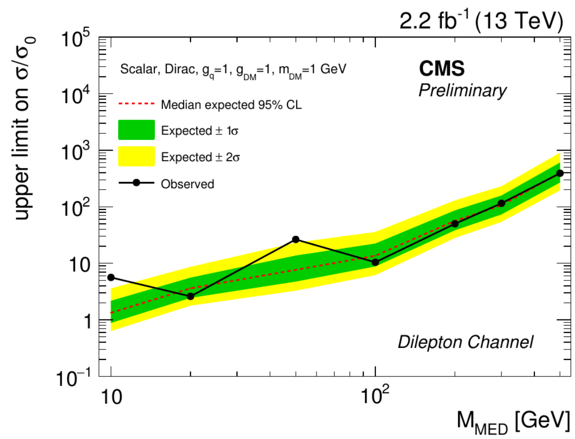


(b)

Figure–2: (a) Limits on the signal strength of $t\bar{t}+$ DM for a scalar DM mediator in the combined hadronic + semileptonic search using 2.2 fb^{-1}. See [2] for details. (b) Limits on the signal strength of $t\bar{t}+$ DM for a scalar DM mediator in the dileptonic search using 2.2 fb^{-1}. See [4] for details.

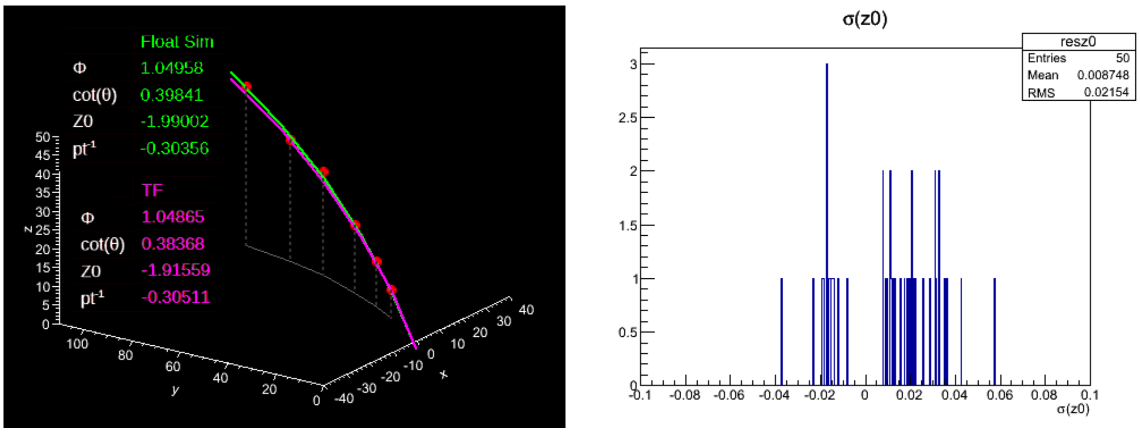
a high level of inter-connectivity for distributed processing. Fermilab has developed an Advanced Telecom Computing Architecture (ATCA) board (the Pulsar2) that can meet these requirements.

The PI has led the development of Pulsar2 Pattern Recognition Board (PRB) firmware for the tracking trigger demonstration. His team completed work on a first prototype of the PRB data distribution firmware in late 2015. This firmware formats stub data received on the PRB's rear-transition module (RTM) and from the ATCA backplane. Formatted stub data is routed either to one of the on-board PRM cards, or to other PRBs in the ATCA crate, to achieve a factor of x20 time-multiplexing. The PRB implementation builds on the group's earlier characterization of the Aurora protocol, an industry-standard, serial transfer scheme designed for low-latency, multi-gigabit communication [5, 6]. The PRB firmware implements $\sim$ 80 independent Aurora links to receive, share and transmit stub data. The prototype firmware was been tested at 300 MHz, and has been shown to achieve a worst-case latency of $\sim 2.0\mu s$ [7]. Further optimization work allowed PRB latency to be reduced to $1.5\mu s$, which greatly relieves timing constraints on downstream processing. The team is now scaling the PRB architecture to the full demonstration system.

The group also developed a prototype version of track fitting firmware, which is based on fitting algorithms developed for the CDF "Level-2" Silicon Vertex Trigger (SVT) [8, 9] and the ATLAS Level-2 Fast TracKer (FTK) projects [10]. Unlike those implementations, CMS track fitting will execute at a much earlier stage of the trigger. Consequently, the latency requirement imposed on CMS L1 tracking is much more severe. The PI's track fit implementation targets the new class of "Ultrascale" FPGAs from Xilinx, which will be deployed on the Fermilab PRM cards for the demonstration.

The team created an IPBus-driven [11, 12], Ultrascale testbench to implement and evaluate the track fitting firmware. The firmware performs track fitting through a series of vector and matrix multiplications, which we have implemented as a multiply/accumulate chain using DSP (digital signal processor) resources on the FPGA. Stub data is input to the hardware testbench using IPBus, the track fit is performed, and output track parameters are read out, again using IPBus.

Figure-3a shows the first muon track fitted in hardware for the AM project. Figure-3b shows the relative difference between the hardware fitted and generated longitudinal impact parameters (z_0) of 50 muons. Both results were produced using our Ultrascale testbench. The track fit executes with a latency of $\sim$ 100 ns [13]. The group also developed an integer emulation of the hardware track fit firmware, and have used this to obtain results that are in excellent agreement with the hardware output.



(a) (b)

Figure–3: (a) Hardware fit (magenta) and generated (green) track trajectories for a single muon passed through our Ultrascale track fitting testbench. (b) The relative difference between the hardware fit and generated track z_0 parameter for 50 hardware fit muons.

Publications, Presentations & Leadership

The group was involved either as lead authors or major contributors in a number of publications and presentations, listed below. In addition to these, the group authored numerous internal CMS notes and presentations, which are not listed. The PI also served in several leadership and advisory roles during the award period.

Publications

1. The CMS Collaboration, "Search for dark matter produced in association with heavy flavor quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV", in preparation for *EPJC.*

2. The CMS Collaboration, "Search for dark matter in association with a top quark pair at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary, CMS-PAS-EXO-16-005.

3. The CMS Collaboration, "Search for dark matter in association with a top quark pair at $\sqrt{s} = 13$ TeV in the dilepton channel", CMS Physics Analysis Summary, CMS-PAS-EXO-16-028.

4. Bauer, M. *et al*, "Towards the next generation of simplified Dark Matter models", arXiv:1607.06680, submitted to *Physics of the Dark Universe.*

5. Boveia, A. *et al*, "Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter", LHC DM WG whitepaper, arXiv:1603.04156.
6. Tristan du Pree, Kristian Hahn, Philip Harris and Christos Roskas, "Cosmological constraints on Dark Matter models for collider searches", arXiv:1603.08525
7. The CMS Collaboration, "Search for New Physics in the V/jet + MET final state", CMS Physics Analysis Summary, CMS-PAS-EXO-12-055, submitted to *JHEP*.
8. "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum", D. Abercrombie, *et al.*, arXiv:1507.00966, (2015).

Presentations

1. Sung, K., "Recent results of searches for BSM physics at CMS", LHC Seminar, CERN, 10/2016.
2. Trovato, M., "Track Finding in CMS for the Level-1 Trigger at the HL-LHC", CHEP 2016, San Francisco, USA, 10/2016.
3. Sevova, S., "Resolved Top Tagger in CMS", BOOST 2016, Zurich, Switzerland, 07/2016.
4. Hahn, K., "DM@LHC: Overview of LHC results on DM", Dark Matter 2016, **invited talk**, Santander, Spain, 06/2016.
5. Hahn, K., "LHC Dark Matter Working Group Summary", QCD and DM at the LHC, **invited talk**, Seoul, Korea, 04/2016.
6. Hahn, K., "The CMS L1 Tracking Trigger Upgrade", ACES 2016 - Fifth Common ATLAS CMS Electronics Workshop for LHC Upgrades, **invited talk**, CERN, 03/2016.
7. Hahn, K., "Status & Outlook of the LHC Dark Matter Working Group", Dark Matter - Cairo, **invited talk**, Cairo, Egypt, 12/2015.
8. Hahn, K., "Searches for Dark Matter with boosted topologies in CMS", BOOST 2015, Chicago, USA, 08/2015.

Leadership and Advisory Roles

- Reviewer for the NSF CAREER Program (10/2016)
- Reviewer for the DOE SCGSR Program (07/2016)
- CMS Analysis Review Committee Chair, "Search for dark matter and gravitons produced in association with a photon in pp collisions 13 TeV", (since 06/2016)
- Reviewer for the Royal Society Research Program (01/2016)
- Co-convener of the Dark Matter Working Group at the CERN LHC Physics Centre (since 11/2015)

- CMS Analysis Review Committee Chair, "Search for monotop in the muon channel in proton-proton collisions at 8 TeV", (since 10/2015)
- Co-convener of the International CMS L1 Tracking Working Group (since 06/2015)
- Member of the USCMS Resource Allocation and Advisory Board (RAAB) (since 05/2015)
- Reviewer for the DOE Scientific Computing Program (04/2015)

References

[1] Sevova, S., for the CMS Collaboration, "Resolved Top Tagger in CMS", BOOST 2016, Zurich, July 2016.
`https://indico.cern.ch/event/439039/contributions/2223296/`

[2] The CMS Collaboration, "Search for dark matter in association with a top quark pair at sqrt(s)=13 TeV", CMS Physics Analysis Summary, CMS-PAS-EXO-16-005, (2016).
`https://cds.cern.ch/record/2204933?ln=en`

[3] Yu, S-S., for the CMS Collaboration, "Search for dark matter in pp collisions with CMS", ICHEP 2016, Chicago, August 2016.
`http://indico.cern.ch/event/432527/contributions/2207061/`

[4] The CMS Collaboration, "Search for dark matter in association with a top quark pair at sqrt(s)=13 TeV in the dilepton channel", CMS Physics Analysis Summary, CMS-PAS-EXO-16-028, (2016).
`https://cds.cern.ch/record/2226566?ln=en`

[5] Hahn, K. *et al.*, "Characterization of the Aurora64b/64b protocol using Pulsar 2a", CMS L1 Tracking presentation, Jan. 2015.
`https://indico.cern.ch/event/366368/contribution/4/attachments/728459/999552/L1AMTrackFindingMeeting01212015.pdf`

[6] `http://www.xilinx.com/support/documentation/ip_documentation/aurora_64b66b_protocol_spec_sp011.pdf`

[7] Hahn, K. *et al.*, "PRB Firmware Update", CMS L1 Tracking presentation, Nov. 2015.
`https://indico.cern.ch/event/461133/session/0/contribution/5/attachments/1185436/1718565/NU_pres_201511.pdf`

[8] The CDF Collaboration, "The CDF Silicon Vertex Trigger," *Nucl. Instrum. Meth.*, **A518** 532-536 (2004). arXiv:physics/0306169

[9] S. Amerio *et al.*, "The GigaFitter: Performance at CDF and Perspectives for Future Applications," *J. Phys.: Conf. Ser.* **219** 022001 (2010).

[10] Shochet, M. *et al.*, "Fast TracKer (FTK) Technical Design Report", CERN-LHCC-2013-007 ; ATLAS-TDR-021.

[11] R. Frazier *et al.*, "Software and firmware for controlling CMS trigger and readout hardware via gigabit Ethernet," *Physics Procedia*, **37** 18921899 (2012).

[12] Hahn, K. *et al.*, "Update on L1Tk Integration Activities", CMS L1 Tracking presentation, May 2014.
https://indico.cern.ch/event/316786/session/1/contribution/15/attachments/608520/837336/l1-tk-2014-05-22.pdf

[13] Hahn, K. *et al.*, "Prototype Track Fitter Firmware for the FNAL Mezzanine", CMS L1 Tracking presentation, Nov. 2015.
https://indico.cern.ch/event/448654/contribution/8/attachments/1186537/1720454/trovato_track_fitter.pdf