Project Title	High Energy Physics Research: Experimental & Theoretical
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FOA Number	DE-FOA-0002832
DOE Program Office	High Energy Physics
DOE Program Technical Contacts	Abid Patwa (Energy Frontier) Brian Beckford (Intensity Frontier) Kathy Turner (Cosmic Frontier) William Kilgore (Theory)
DOE Award Number	DE-SC0017647
PAMS LOI Number	LOI-0000040178
Research Areas	Energy Frontier Cosmic Frontier Intensity Frontier Theory

High Energy Physics Research: Experimental & Theoretical

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Abstract

This proposal is to conduct research at the Energy, Intensity, Cosmic, and Theoretical frontiers of high energy physics. The group works on: ATLAS, CMS (Energy); MINOS+, NOvA, DUNE (Intensity); DES, VRO (Cosmic); Phenomenology, String Theory, Computational and Theoretical Cosmology (Theory). The mission of our High Energy Physics (HEP) program is to understand how our Universe works at its most fundamental level.

The UW-Madison group works on all five intertwined science drivers of particle physics that are identified as providing compelling lines of inquiry with great promise for discovery: 1) use the Higgs boson as a new tool for discovery (Energy) 2) pursue the physics associated with neutrino mass (Intensity) 3) identify the new physics of dark matter (Energy, Cosmic) 4) understand cosmic acceleration: dark energy and inflation (Cosmic, Theory) 5) explore the unknown: new particles, interactions, and physical principles (All).

The group will employ methods such as 1) studies of high energy proton-proton collisions using general purpose detectors with particle trackers and calorimeters aided by sophisticated trigger electronics and computing systems (ATLAS and CMS), 2) studies of neutrino interactions in large liquid scintillator (NOvA) and liquid argon time projection chamber (DUNE) detectors, 3) wide-area imaging surveys using optical telescopes (DES and VRO) to study the dark energy, dark energy and inflation, and 4) computational and mathematical methods of quantum field theory and string theory (Theory), which underpin the theoretical framework that enables us to understand our Universe at a fundamental level. The group conducts several seminars jointly, seeding and encouraging collaboration, and participates in academic evaluation of each other's graduate students.

The impact of our research is to extend the collective knowledge of high energy physics and astrophysics phenomena, and to understand fundamental aspects of the particles and forces in Nature. The proposal has substantial impact in areas identified by the DOE as key research directions. The adaptation of the new electronics technologies in this proposal could also lead to future development of medical imaging, detector signal processing and advances in image processing. Influx of complex data from our particle physics research, and the new astrophysical wide-area surveys, requires big data processing and analytics; these technologies have a direct impact on other areas of scientific research and commercial applications, and provide well-trained personnel to the community. The group is strengthened by collaborations with the campus-wide community in data science, computing, and mechanical and electrical engineering.

1 Overview

The University of Wisconsin group of Professors Kevin Black, Tulika Bose, Sridhara Dasu and Matthew Herndon proposes to continue its active leading roles in the Compact Muon Solenoid (CMS) experiment [1] at the LHC, as we explore proton-proton collisions at 13 TeV and prepare for future higher luminosity running. Presently the UW group includes Senior Scientists Alexander Savin, Pieter Everaerts, Assistant Scientists Isabelle De Bruyn, Deborah Pinna, Varun Sharma, Postdocs Camilla Galloni, Charis Koraka, Lecturer Abdollah Mohammadi, six women, seven male and one non-binary graduate student(s), supported by seven engineers and computing experts. The group is welcoming to all genders and members of the LGBTQ community.

The UW group is leading physics analyses in characterization of the Higgs Boson, searches for its potential partners, searches for particle dark matter, potential signatures of new physics in processes involving heavy quarks - top and bottom, and extensive studies of the electroweak processes. The UW group built, commissioned, operates, and upgrades major parts of CMS: the trigger system, including the Level-1 (L1) trigger and higher level triggers (HLT), the endcap muon system (EMU), including its infrastructure, cathode strip chambers (CSCs) and the new Gas Electron Muliplier chambers (GEMs), software for simulation and event processing, and a leading Tier-2 computing facility. The experiment service responsibilities of the group members are closely tied to their physics analysis interests and leadership. Table 1 lists current group management positions. References provide the list of papers that the UW group contributed directly.

1.1 Group History

The CMS group at Wisconsin was founded by Professors Don Reeder, Wesley H. Smith and then scientists Richard Loveless and Sridhara Dasu in 1993. Prof. Wesley H. Smith, American Physical Society's Wolfgang Panofsky Award winner, was the leader of the group up until his early retirement four years ago. Prof. Matthew Herndon joined the group in 2010 and Prof. Kevin Black and Prof. Tulika Bose in 2018. After helping build, commission and operate the detector, the group is playing strong roles in electroweak, higgs and new physics analyses, graduating 24 PhD students and mentoring 12 postdocs/scientists. Of particular note are the five women postdocs/scientists who moved on with success, securing faculty/scientist positions at prestigious places around the world.

1.2 Proposed Research Directions

The primary mission of the LHC is the search for new physics, such as discovering the nature of dark matter, exploring the possible unification of the forces, and resolving the hierarchy problem. This involves seeking a deep understanding of the Higgs boson characteristics and the mechanism of electroweak symmetry breaking and exploring if the Higgs boson has partners. Searches for small deviations from the Standard Model predictions for processes involving multiple vector bosons or heavy quarks are particularly interesting. The UW group plans to continue its study of the SM Higgs boson and explore the nature of electroweak symmetry breaking using vector boson scattering, where the Higgs boson plays an essential role in unitarizing the cross section. We will also search for additional Higgs bosons or new vector bosons that are typically part of Unification models with larger gauge groups that would have a strong effect on vector boson scattering. To explore the nature of dark matter the UW group has initiated a number of searches, which look for large missing transverse energy produced in association with SM particles such as photons, Z bosons, Higgs bosons and top quarks. The group is also expanding its physics effort to search for vector-like leptons, low mass exotic quark bound states and multiple top quarks production.

Name	Unit	Level	Position
Prof. Kevin Black	USCMS	-	LPC Co-coordinator
	CMS	Level-2	GEM Electronics Coordinator
	USCMS	Level-3	GEM Electronics Project Manager
	CMS	Level-3	GEM Review Coordinator
Prof. Tulika Bose	CMS	-	Member, Collaboration Board
	USCMS	Level-1	Deputy Manager, Software & Computing
Prof. Sridhara Dasu	CMS	-	Member, Collaboration Board
	USCMS	Level-3	Manager, HL-LHC Calo Trigger Upgrade
Prof. Matthew Herndon	CMS	Level-3	CSC Resource Manager
Senior Sci. Sascha Savin	CMS	Level-3	Co-convener, HL-LHC Calo Trigger Upgrade
Asst. Sci. Isa De Bruyn	CMS	Level-3	CSC Run Coordinator
	CMS	Level-2	Muon Upgrade Coordinator
Asst. Sci. Deborah Pinna	CMS	Level-2	Co-convener, B2G Physics Analysis Group
Asst. Sci. Varun Sharma	CMS	Level-3	Co-convener, SUS PAG Had/Photon Subgroup
Postdoc Camilla Galloni	CMS	Level-3	GEM Run Coordinator
Lecturer A Mohammadi	LHC	-	Co-convener, WG3: BSM Higgs Subgroup

Table 1: CMS and US CMS management positions held by the UW group members. The level of positions in the CMS or US CMS org-charts is indicated, where applicable.

The LHC operations are classified as Run-1 (2009-2012, 7-8 TeV center-of-mass energy, 36 fb^{-1}), Run-2 (2015-2018, 13 TeV, 160 fb^{-1}) and Run-3 (2022-25, 13.6 TeV, 40 fb^{-1} in 2022 with >300 fb^{-1} expected). The UW group led several Run-1 analyses establishing the SM at the LHC and had a thumping success of the discovery of the Higgs boson. They followed up with initial Run-2 analyses, which firmly established the Higgs and set stringent constraints on new physics processes. The exploitation of the full Run-2 dataset remains in our focus, while the Run-3 analyses are beginning.

The complexity of physics signatures, backgrounds, detector conditions of full Run-2 data already mandates us to investigate multi-variate techniques using Machine Learning (ML) tools. The UW group has deployed some ML techniques in its analyses and even trigger hardware, as outlined below. The group is playing leading roles in software and computing using GPUs both for high-level trigger usage and successful execution of ML techniques, which are very resource intensive.

The Run-3 began operating at 13.6 TeV center-of-mass energy earlier this year. The UW group work during the long shutdonw 2 (LS2) in preparation for the Run-3 involved, EMU CSC chamber upgrades, new EMU GEM chambers, trigger firmware improvements, and HLT menu development and commissioning. The (re)commissioning and diligent preparation for data quality monitoring have paid off well. Good quality data collection is underway leading to an accumulation of about 40 fb^{-1} in recently concluded 2022 run. Analyses are being prepared using improved smaller sized data formats such as the nano-AOD, using Run-2 data. The group anticipates to move on to Run-3 analyses when about 100 fb^{-1} are collected in 2023. Year 2022 already saw long periods of increased level of instantaneous luminosities, upwards of $2 \times 10^{34} cm^{-2} s^{-1}$, resulting in sustained stressful pileup conditions. One of the major remaining challenges is to continue to take data of importance at the electroweak scale under these adverse conditions. Therefore, further trigger improvements are being prepared for 2023 operations. For instance, we have implemented a boosted jet trigger. We have also made improvements using event-wide calorimeter information in the spare capacities available in our FPGA trigger platform. We are commissioning these ML applications in FPGA firmware using High-Level Synthesis (HLS). We are also upgrading our HLT code to use GPUs.

One of the goals of the group is to prepare for the HL-LHC program, i.e., Run-4-and-beyond, by experimenting with and perfecting the ML techniques in physics analyses and trigger using the ongoing full Run-2 data analysis and Run-3 developments. Some of the work involves extensive simulations and usage of new computing resources with GPU and FPGA assisted environments.

The UW CMS group has a long tradition of providing its share of experiment support both in terms of maintenance and operation of the muon detector and the trigger systems. The group proposes to fully participate in acquiring the Run-3 data with personnel located on site at CERN. The group also maintains, operates and upgrades a productive Tier-2 computing center for CMS at Madison, which has recently been augmented with the largest GPU resources amongst the US Tier-2s. The group also took important roles in the GPU software development and deployment.

The UW CMS group also plays leading roles in the upgrades. The CSC chamber electronics were upgraded during LS2 and GEM chambers are being built and furnished with electronics on-site at CERN, and the trigger electronics for HL-LHC are being produced in Madison. Senior group members play both management and supervisory roles. The detector qualification, calibration, software and firmware work associated with these upgrades involve group physicists.

2 Physics Analysis Activity

2.1 Overview

Our primary physics activities are the study of electroweak symmetry breaking mechanism, searches for associated new physics phenomena, searches for the source of particle dark matter and other exotic phenomena. The 2012 discovery of the Higgs boson[2, 3], in which our group played an important role, sets the context for our current and future research program. It strengthens the case for detailed study of the EWSB mechanism both by measuring the properties of the new boson and by investigating multiple-gauge-boson production. Our flagship analyses include leading contributions to the observation of Higgs coupling to fermions via τ-lepton pairs [4] and also to the Higgs discovery decay mode into four leptons [5]. We have since used Higgs as a new physics discovery tool by searching for dark matter produced in its recoil [6, 7], bosons of extended higgs sectors [8, 9, 10, 11, 12, 13, 14] and lepton-flavor violating decays [15, 16, 17, 18]. We have also conducted dark matter searches in recoils [19, 20, 21, 22, 23, 7, 6, 24, 25] from jets, photons, Z-bosons and top-quarks. Our electroweak physics analysis effort has resulted in papers on vector boson with heavy flavor production, di-boson production and searches for anomalous triple and quartic gauge boson couplings. Our searches and measurements in SM Higgs and vector boson physics have been leveraged into new physics searches in similar topologies.

We strive to maximize both physics output and variety. Prof. Herndon and Senior Scientist Savin focus on supervision of the SM measurements and associated new physics phenomena. Prof. Dasu works with Assistant Scientist Sharma, focusing on SM Higgs characterization, new physics in the Higgs sector and dark matter searches. Prof. Bose works with Assistant Scientist Pinna and Postdoc Koraka on searches for heavy new particles involving heavy quarks, vector-like leptons, resonances of higgs pairs, and dark matter. Profs. Black works with Senior Scientist Everaerts and Postdoc Galloni on the study of processes involving LFV higgs, exotic quark-gluon bound-states and displaced tracks, looking for signatures of new physics, and exotic triple top quark final states.

Scientists Savin and Sharma (Level-1 trigger), Pinna (High Level Trigger) and Everaerts and De Bruyn (EMU), all based onsite at CERN, supervise student work on detector, electronics and software/computing issues, ensuring that high quality physics is enabled with smooth operations, and that potential upgrades are thoroughly vetted and realized during LHC shutdown periods.

We require our graduate students to make a measurement in the context of the Standard Model and also search for new physics in similar final states, as well as receiving well-rounded training spanning vital experimental service roles. They also participate actively in the collaboration reviews of analyses. UW group members routinely serve in the physics organization senior management. Detailed listing of current positions they hold are listed in Table 1. A table of past positions held by the group members is in the Appendix.

2.2 Electroweak Physics

Measuring SM electroweak (EWK) processes is essential to understanding the gauge sector of the SM and further exploring the mechanism of electroweak symmetry breaking. Our group has continuously held leadership positions in the SMP group (past conveners Dasu and Savin) and is responsible for many important SM measurements at 13 TeV, and associated searches for new physics. Our contributions were crucial for CMS measurements of Z to $\ell^+\ell^-$, W+jets, Z+jets, W+charm, W+b, γ+jets, Zγ, WZ and ZZ cross sections. Recently the UW group has focused on both SM and new physics in multi-boson physics in the WZ and ZZ states.

2.2.1 Di-boson Physics

The UW group has a strong effort in analysis and leadership in the multi-boson subgroup (past conveners Herndon, Duric, Long). UW analysis projects include QCD induced di-boson production and EWK production of both single and multiple heavy gauge bosons. The measurements encompass production cross sections, differential cross sections, anomalous triple gauge couplings of vector bosons (aTGCs), anomalous quartic gauge couplings (aQGCs), and the study of the pure EWK production mechanisms such as vector boson scattering and fusion. Many of these analyses have connections to both Exotica and Higgs physics searches for resonant decay to pairs of vector bosons as well as dark matter searches in vector boson production with missing energy topologies.
WZ and ZZ production in SM and anomalous couplings: The UW group has previously measured cross sections and analyzed anomalous couplings at 7 and 8 TeV for Zγ, WZ and ZZ di-boson production and performed the first measurements of the WZ [26] and ZZ [27] production at 13 TeV and further measurements of the properties of WZ [28] and ZZ [29] [30] production with the early Run 3 data. Graduate student Long (Advisor Herndon, Ph.D. 2019) with Scientist Savin performed a search for EWK WZ production and quartic gauge coupling and in WZ vector boson scattering and an associated search for charged Higgs produciton via vector boson fusion [31]. Following this, graduate student Hussain (Advisor: Dasu, Ph.D 2019) with Long, Prof. Herndon and Dr. Savin have produced a cross section measurement and a complete set of differential cross section measurements and also anomalous coupling constrains using the full Run 2, 13 TeV dataset [29]. The analysis was one of the first using the full Run 2 data set and achieved 3.7% uncertainty making it one of the LHC's most sensitive cross section measurements. Graduate student Mondal (Advisor Herndon) wrote Rivet routines (now in review) for the publication of this data. Graduate student He (Advisor Herndon) with Dr. Savin worked on researching a deep NN (DNN) for the discrimination of EWK ZZ production as an alternative to the standard method and participated in the ZZ analysis that achieved evidence for purely EWK production of ZZ diboson pairs through electroweak scattering [32]. Graduate student He, scientist Savin and Prof. Herndon are extending the ZZ measurements to include differential measurements vs. the number of jet produced in ZZ production and and also subdividing the 4 lepton invariant mass space in different

regions [1] [33]. This analysis is in review before the final approval and a complete paper draft will soon go into review for publication. In addition, graduate student Mondal has produced NNLO comparisons for inclusion in this paper. These type of measurements should be performed in all di-boson production and decay modes and with undergraduate Downham and Prof. Herndon studied the statistical sensitivity of each of the QCD induced and EWK di-boson production and decay modes to understand the best prospects for further studies [33].

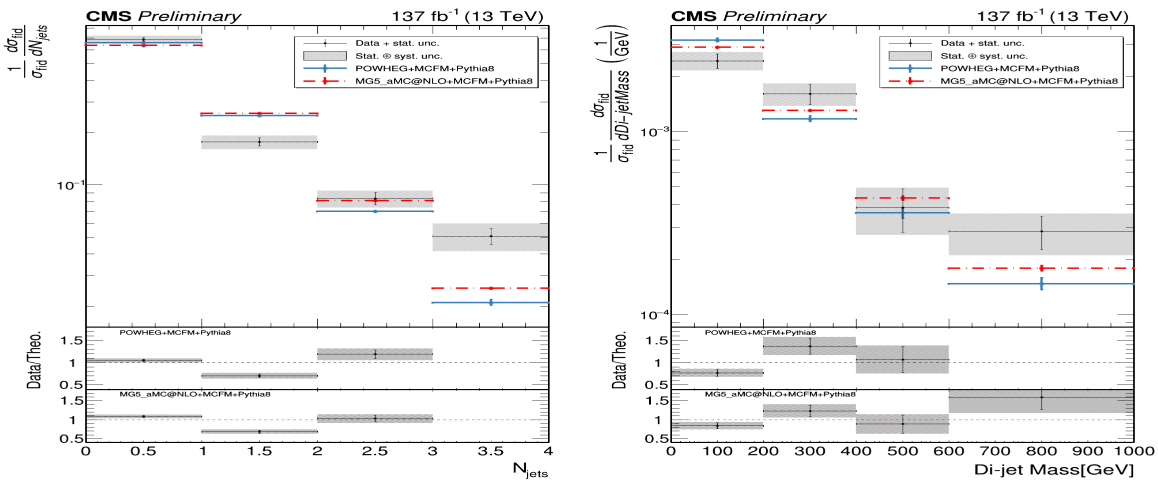

Figure 1: From the ZZ+jets analysis. Distribution of jets in 4l events(left). DiJet mass distribution in 4l event(right). (He & Savin)

2.2.2 Proposed research: QCD & EWK multi-boson production & polarization.

Integral to searching for di-boson production though purely EWK scattering is studying the polarization of the scattered vector bosons to disentangle the contributions of longitudinal vector boson scattering via the Higgs from scattering via vector bosons or quartric gauge boson interactions. New physics can contribute strongly in vector boson scattering and polarization information can distinguish between scattering via new vector particles, as might be expected in Unification theories which expand the the SM gauge group, and new scalar particles, such as additional Higgs bosons or other scalars. The UW group has developed substantial expertise in EWK di-boson production searches through graduate students Long and He's analysis with Prof. Herndon on EWK production in the WZ S [31] and ZZ [32] final states. Building on the WZ work graduate student Teague (Advisor: Black) with Long, Prof. Herndon and Dr. Savin studied the potential of the full HL-LHC dataset to measure EWK WZ production and study polarization [34]. Graduate student Mondal will perform her thesis research on measuring the polarization of Z bosons in ZZ production and an analysis of the dependence of polarization on the energy of ZZ pairs. Graduate student Marquez (Advisor Herndon) is studying using polarization and other angular or energy dependent variables to enhance the sensitivity of ZZ data to anomalous couplings. Marquez and Prof. Herndon intend to perform a study of all standard model effective field theory operators (SMEFT) the can contribute to ZZ production. Different operators can be associated with specific final state vector boson polarization making polarization angles a powerful discriminate for differentiating new physics EFT operators. New MCs that allow tracking of polarization information and NLO generation are essential to these studies. The UW group proposes to first study polarization in QCD ZZ production using the Run 2 dataset. Then those techniques, combined with ML algorithms, will be extended to look for EWK production and study the longitudinal scattering component via the Higgs boson and new physics using the combined Run 2 and Run 3 data-sets and beyond. Scientists Savin, Sharma and Dasu are proposing to measure tri-boson production, including τ modes capitalizing on their expertise.

2.3 Higgs Physics

2.3.1 Higgs Decays to Z pairs in lepton modes

Profs. Dasu, Smith and Scientist Savin contributed to the analysis of Higgs decays to Z-pairs in the four-lepton mode over the years. Our contribution to ZZ analysis [5] helped to firmly establish the nature of the H(125), its mass, spin-parity and its vector-boson coupling. Earlier graduate students Ross (Ph.D. 2013, Advisor: Dasu), Belknap (Ph.D. 2014, Advisor: Smith) and Woods (Ph.D. 2017, Advisor Smith) obtained their PhDs based on this work. This work involved collaboration with Florida, JHU, Caltech and many European groups.

2.3.2 SM Higgs Decays to tau pairs

The SM decay $H \to \tau\tau$ provides access to the Higgs Yukawa couplings to the lepton sector. The UW team of graduate students Bachtis (Ph.D. 2012, Advisor: Dasu), Swanson (Ph.D. 2013, Advisor: Smith), Ojalvo (Ph.D. 2014, Advisor: Smith), Levine (Ph.D. 2016, Advisor: Dasu), Loeliger (Ph.D. 2022, Advisor: Bose), former postdocs Friis, Ojalvo, Caillol (Advisors: Dasu & Smith) and Scientist Savin made extensive contributions [4] to CMS body of work on Higgs boson decays to tau pairs, using $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ modes, with boosted, Vector Boson Fusion (VBF) and Vector Boson associated (VH) Higgs production categories, using Run-1 and Run-2 data. CMS success in this effort was due to our comprehensive work ranging from triggers and reconstruction as evidenced by sustained leadership of the Tau Physics Object Group (Past Conveners: Savin, Friis, Caillol & Ojalvo) and the H2Taus Physics Analysis Group (Past Convener: Dasu & Caillol). Bachtis' thesis won the CMS 2012 best thesis award, and the Hadrons-Plus-Strips (HPS) algorithm still remains the basis of τ_h-reconstruction. Caillol won the CMS 2017 best thesis award as well. The Run-2 (2016-only) analysis led by former postdoc Caillol involving students Dodd (Ph.D. 2018, Advisor: Smith) and Ruggles (Ph.D. 2018, Advisor: Dasu) involved many channels and categories jointly analyzed, culminated in a 5σ observation [4] of the Higgs boson decays to τ-pairs. Recent PhD graduate Loeliger (Advisor: Bose) and former Postdoc Caillol (Advisor: Dasu) collaborated with colleagues from Princeton, KSU and JHU to finalize the full Run-2 results including the addition of VH production modes [35], extraction of the fermion and vector boson Higgs couplings [35] and measurement of differential kinematic distributions [36] (See Figure 2).

2.3.3 Recent Results: Lepton Flavor Violating Higgs Decays

Lepton flavor conservation in the Standard Model is accidental. Charged lepton flavor violation in their Yukawa couplings to Higgs can be directly tested at the LHC. Graduate student Levine (Ph.D. 2016, Advisor: Dasu) and former postdoc Cepeda observed a small excess (2σ) in lepton flavor violating $H \to \mu\tau$ decay using Run-1 data [15, 16], resulting in much speculation by the theory community. A quick follow up using early Run-2 data by former Postdoc Calliol indicated that it is most probably a statistical fluctuation [17]. Asst. Sci. Sharma, in collaboration with Notre Dame and CERN groups, completed a comprehensive Run-2 analysis [18], looking in to $H \to \mu\tau$, $H \to e\tau$ and $H \to e\mu$ modes, showing no excess resulting in the limit parameter scans ($H \to \mu\tau$ results are shown in Figure 3).

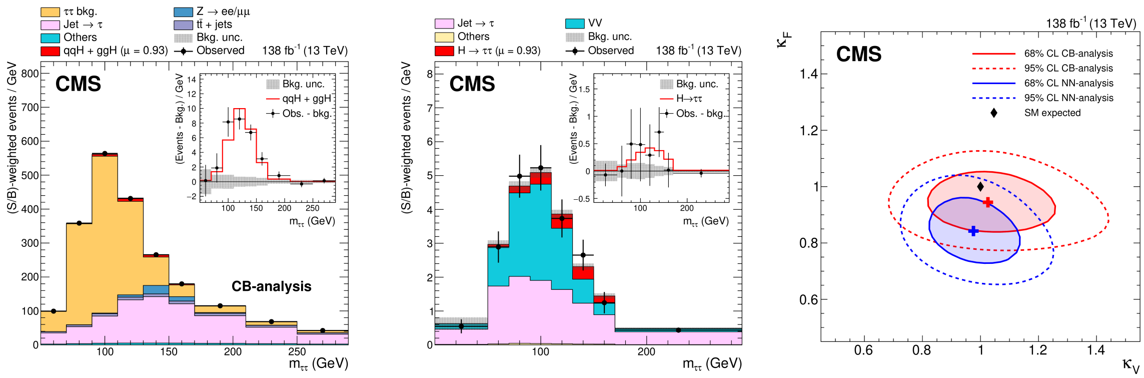

Figure 2: $M_{\tau\tau}$ distribution with an inset showing the $H \rightarrow \tau\tau$ signal (left). Mass distribution for ZH mode (middle). Vector and fermion coupling constraints extracted from a fit to all production modes and τ-pair decay channels for cut-based and NN analyses (right). (Loeliger & Caillol)

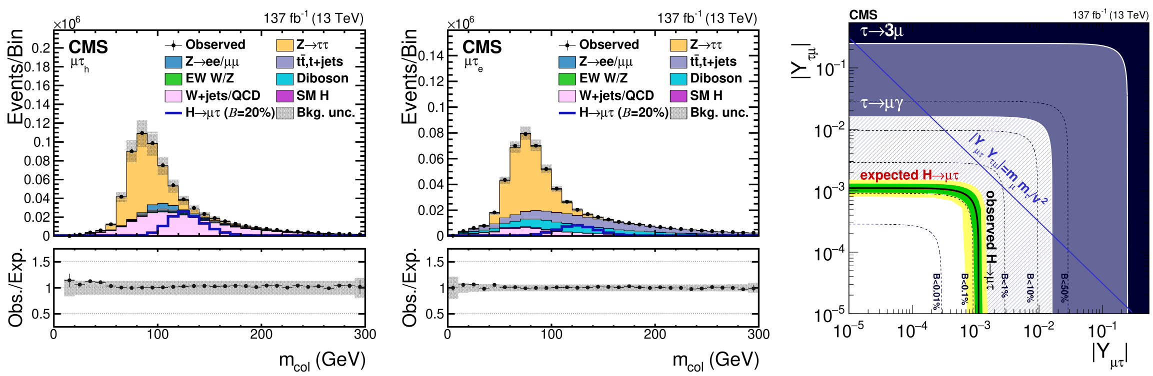

Figure 3: Collinear mass spectrum of $\mu\tau_h$-system (left), $\mu\tau_e$-system (center), and constraints on the extracted non-SM Yukawa cross-couplings. (Sharma)

2.3.4 Current Research: Light Pseudo-scalar Higgs

The next-to-minimal super symmetric standard model (nMSSM) and generic models with two higgs doublets and a scalar (2HDM+S) contain a light pseudo-scalar Higgs boson called the a-boson, which decays to a fermion pair. These models have attractive theoretical features eliciting our interest. The a-boson is often produced in h(125) decays with significant branching fraction. Former Postdoc Caillol had completed a search for this a-boson in the modes $h \rightarrow aa \rightarrow \tau^+\tau^- b\bar{b}$ using partial Run-2 data [10]. Results from the full Run-2 data (See Figure 4) by graduate student Tsoi (Advisor: Dasu) and Scientist Everaerts, which further restricted the model parameter space, is in final stages of review in the collaboration. This analysis involved low p_T final-state τ-leptons, presented an analysis challenge, and was tamed using ML techniques. Graduate student Aravind (Advisor: Black) and Scientist Everaerts are extending the analysis to the other modes.

Probing the remaining parameter space using Run-3 data, presents a major level-1 trigger challenge, requiring multi-object event-level correlations. Graduate Students Tsoi and ECE student H. Sharma (Advisor: Dasu) have used ML techniques to build calorimeter trigger firmware, in collaboration with Princeton group. Scientists Sharma and Savin are working with our engineers to deploy an additional electronics board running this firmware in Run-3 trigger system. This ML-based level-1 trigger provides higher efficiency not only for this process but also for a plethora

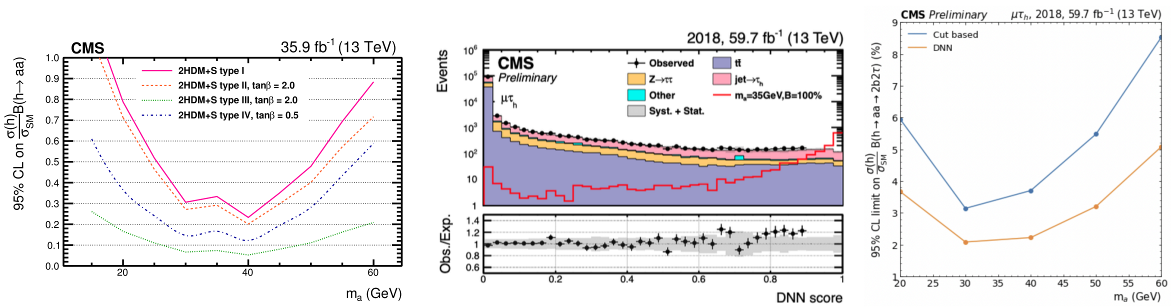

Figure 4: Previously published 95% CL limits on exotic $H \to aa$ branching fraction for various 2HDM+S models with 2016 data (left). Deep neural network discriminator distribution for $H \to aa$ compared to backgrounds for 2018 data. (middle). Expected improvement due to the use of ML techniques (right). (Tsoi & Caillol)

of others involving production of correlated low E_T clusters.

2.3.5 Current Research: Searches for new physics in DiHiggs production

Graduate Student Parida (Advisor: Bose) is searching for narrow high-mass resonances in di-higgs ($b\bar{b}\tau^+\tau^-$) production with Postdoc Galloni (Advisor: Black), who was the author of several boosted diboson searches [37, 38]. While SM diHiggs production is a direct measurement of the Higgs self-coupling and critical to understanding the shape of the Higgs Boson potential, the cross-sections are so small that it is expected that it will not be observable until the full HL-LHC dataset is analyzed. However, several viable BSM models predict heavy resonances decaying into pairs of Higgs Boson pairs. Examples include Kaluza-Klein (KK) excitations of spin-0 radions or spin-2 gravitons. For the TeV mass scales explored, dedicated substructure and reconstruction techniques are a must. Our group is building upon Galloni's boosted tau reconstruction [39] by developing a dedicated algorithm for identifying boosted taus using deep learning techniques. Initial work on this algorithm was done by Loeliger for his thesis and is now being pursued by Parida (Figure 5). Upon completion of the full Run 2 dataset analysis, our team will explore adding new triggers for Run 3 and explore additional ML-based approaches for optimizing the signal and background discrimination using the Run 3 dataset.

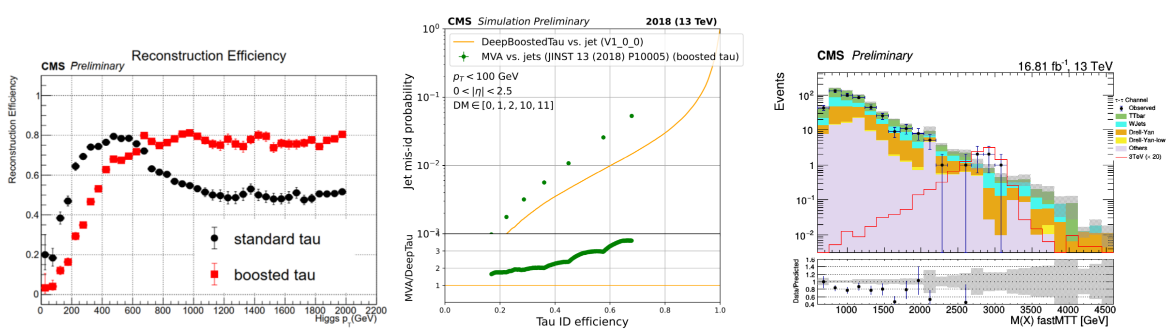

Figure 5: Improvement in the reconstruction efficiency coming from Dr. Galloni's boosted tau reconstruction (left), preliminary ROC curves for the DeepBoostedTau identification algorithm being developed by our group (middle), and resonance mass distribution shown using loose pre-selection requirements (right). [Galloni, Loeliger, Parida]

2.3.6 Proposed Research: Invisible Higgs Decays

There is a large range of parameter space in several new physics models, e.g., MSSM, where there exists a h(125) that can decay invisibly. Current accuracy of the LHC datasets allow significant room, amounting to a 20% branching ratio of h(125) to invisible states. A search for such decays is also motivated by the possibility of a discovery of a dark matter particle candidate through this Higgs portal. The group had earlier searched for invisible decays of h(125) which is produced in association with a Z-boson, that is reconstructed in its leptonic decay modes [23]. The analysis is limited by statistics and we propose to analyze Run-3 data, in both easy to trigger Z-associated production and the more difficult to trigger Vector Boson Fusion mode. The ML-based level-1 trigger being implemented for Run-3 will likely enhance our sensitivity.

2.3.7 Proposed Research: MSSM Higgs Decays to tau pairs

For certain regions of parameter space, neutral heavy MSSM Higgs bosons decay preferentially to τ-pairs. The UW team of Bachtis (Ph.D. 2012, Advisor: Dasu), Ojalvo (Ph.D. 2015, Advisor: Smith), Dodd (Ph.D. 2018, Advisor: Smith) and Ruggles (Ph.D. 2018, Advisor: Dasu), Senior Scientist Savin and postdocs Friis, Ojalvo and Caillol used both Run-1 and Run-2 data over the past years to search for neutral heavy Higgs bosons [12, 13, 14]. There is a wedge of unexplored area in the $m_A - \tan\beta$ plane, which is limited by the available statistics. Much like in the SM $H \to \tau\tau$ case, we propose to improve tools to search for these heavy states awaiting the Run-3 data accumulation.

2.3.8 Proposed Research: Higgs Precision Physics

Measurement of SM Higgs couplings to percent-level precision is amongst the most important goals of the HEP community. Any deviations at percent level from the SM expectations lead to the establishment of new physics scales of O(10) TeV. Therefore, Prof Dasu and the team, will continue their strong role in Higgs physics. We anticipate new results of relevance will be possible with the full Run-3 data. In the coming two years they propose to develop improved analyses to obtain the best differential cross section and polarization measurements. This program will continue through HL-LHC resulting in publications whenever accumulating data doubles.

A lepton-collider higgs factory is necessary to get down to percent-level precision across the board. Triple and quartic higgs couplings measurements require a 10-TeV scale muon collider. Participation in design concepts and optimizing the detectors are a major task. The UW group has begun its involvement with significant participation in both Cool Copper Collider [40] and Muon Collider [41] programs.

2.4 Dark Matter Searches

Weakly interacting massive particles are among the most favored candidates for explaining the overwhelming evidence for dark matter in our universe, which is established using its gravitational interactions. If the dark matter (DM) is made of particles, which are light enough and interact with sufficient strength with normal matter, the LHC should be able to produce them in proton-proton interactions. However, the dark matter particles will escape the CMS detector leaving no trace. Nevertheless, one can search for such dark matter particles produced in reactions with initial state radiation that recoils from the dark matter candidate. Portals to dark matter comprising the Higgs boson or hitherto unknown force particles are also possible. Models of interactions mediated by a new scalar and/or pseudoscalar have become popular recently – they are theoretically well-motivated and can be easily accommodated in extended Higgs sectors. Assuming minimal flavor violation, the couplings between the neutral spin-0 mediator and the SM particles are proportional to the fermion masses motivating searches for DM in association with top.

Our group continues to have leadership roles in this area with Asst. Sci. Sharma recently appointed as the co-convener of the SUS photons, hadrons and jets with MET subgroup, following Asst. Sci. Pinna and former postdoc B. Gomber, who have published several DM searches [6, 7, 19, 20, 21, 22, 23, 24, 25] and had led the "MET+X" sub-group within the Exotica Physics Analysis Group (2018-2020).

2.4.1 Current Research: Mono-jet and Mono-light-Z' Search

Graduate student Mallampalli (Advisor: Dasu) and Asst. Sci. Sharma had searched for mono-jet signature using the full Run-2 data [25] in collaboration with Boston group. The MET distribution in mono-jet events shown in Figure 6 is in agreement with the sum of all SM contributions. Constraints on parameter space of WIMP dark matter and other possible models are now published. Mallampalli has moved on to a search for a distinctive signature of mono-light-Z' boson production. A weakly interacting dark matter particle candidate, which interacts with the standard model fermions through a very weakly coupling light vector boson (Z') boson is pioneered by Prof. Yang Bai (UW) and collaborators. In such a model, there appears a distinctive pencil-thin jet recoiling from a large missing transverse energy. Mallampalli has produced initial results which extend the mono-jet search significantly. Significance for mono-Z' improves by a factor of 3 compared to using mono-jet like cuts, by using the distinctive features of pencil-thin jets and a dense neural network. Internal review of this analysis is beginning.

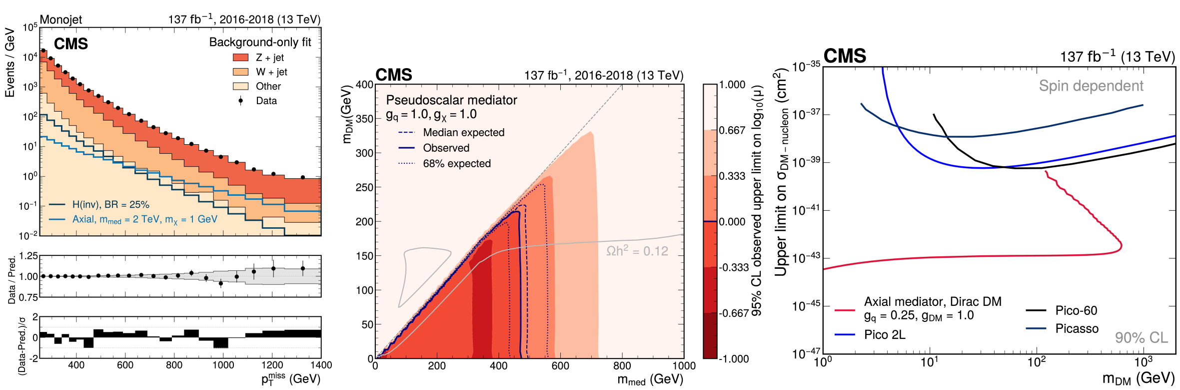

Figure 6: MET distribution for mono-jet data showing good agreement with SM showing no evidence for invisible Higgs decays or WIMP production mediated by heavy particles (left) Constraints on mediator and WIMP candidate mass (middle) Comparison to direct-detection experiments (Mallampalli & Sharma).

2.4.2 Current Research: Boosted H and Mono-H Analysis

Potential connection of the Higgs boson with dark matter is an especially important case to study. In some new physics models, an additional Z' boson exists and decays primarily to the SM-like Higgs boson, H(125 GeV) and a heavy virtual Higgs boson (e.g., the heavy pseudo-scalar A in 2HDM). The virtual A in turn decays primarily to a pair of weakly interacting massive particles,

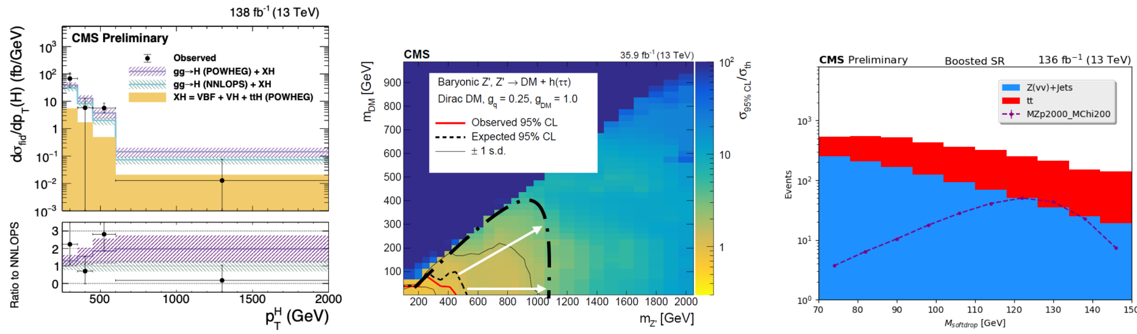

Figure 7: Boosted $H \to \tau\tau$ P_T distribution (Mohammadi) (left) Mono-higgs ($\tau\tau$) search results showing the expected improvement with full Run-2 data (136 fb^{-1}) is shown as black-dot-dash curve (Jithin Ph.D. 2022) overlaid on the published 2016 (Dodd Ph.D. 2019) (middle) Simulated boosted mono-higgs (b-jet pair) sub-jet mass distribution is show compared to the backgrounds (Lomte) (right).

which are dark matter candidates. Another model uses a baryonic-Z' as mediator. Early results from Run-2 data [7], are recently updated using the full Run 2 dataset, in the $H \to \tau\tau$-mode by the recent PhD Jithin Sreekala (Advisor: Dasu) [42]. The key recent addition to this analysis is the use of boosted di-τ pair reconstruction pioneered by Lecturer Mohammadi, which he used for boosted Higgs P_T measurement shown in Figure 7 along with the reach for baryonic-Z' model. Both analyses are under review within the collaboration. Graduate student Lomte (Advisor: Dasu) and Asst. Sci. Sharma are also working on analyzing resolved and boosted $H \to b\bar{b}$-modes, which are expected to have much higher significance. MC study indicates that the coverage can extend to $M_Z' = 2$ TeV, $M_\chi = 200$ GeV. Further, note that the new Run-3 trigger improvements with boosted Level-1 jets and τ-pairs, developed in collaboration with Princeton, will likely enhance the reach significantly using Run-3 data.

2.4.3 Current Research: Top + Dark Matter Analyses

Graduate student Shang (Advisor: Bose) and Asst. Sci. Pinna have produced full Run-2 results for dark matter produced in association with single-top and $t\bar{t}$. This result builds upon previous work done by Dr. Pinna who has been one of the leading contributors to the CMS analyses performed using the 2015 and 2016 datasets [20, 43]. This includes an extension of the $t\bar{t}$+DM analysis to include single top + DM, which was performed for the first time at the LHC and resulted in an improvement of up to a factor of two with respect to previous published limits on scalar and pseudoscalar interactions [24]. The full Run 2 analysis includes, for the first time, events where two leptons are produced from the decay of the W bosons. Additionally, Shang and Dr. Pinna have exploited new discriminating variables based on signal topology for dedicated event categorization. Further improvement in sensitivity stems from the higher statistics available in the control regions, where the backgrounds were estimated from data, allowing better constraint on the systematic uncertainties affecting shape and normalization of the missing transverse momentum spectrum. Overall, the improvements lead to results which are better by about 30% with respect to the increase in sensitivity coming from simply adding more data (Figure 8). CMS internal review of this analysis is underway and a publication is expected in the next few months.

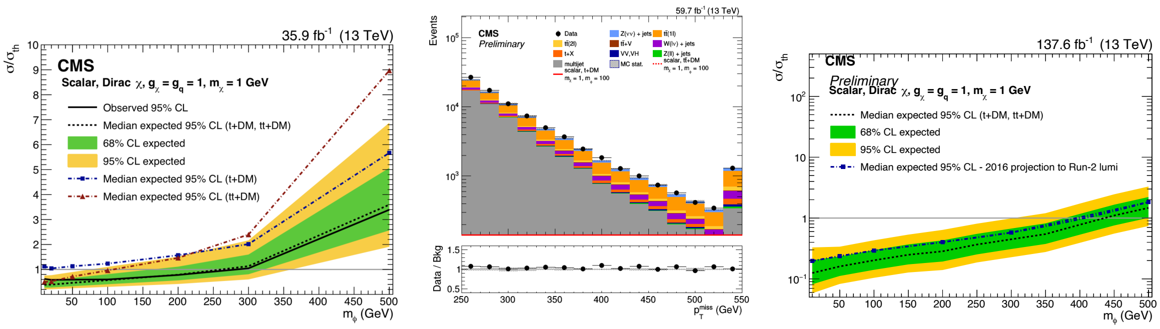

Figure 8: Expected and observed 95% CL upper limits for $t\bar{t}$+DM and t+DM together with their combination (left) for the 2016 analysis [Pinna]. The missing transverse momentum distribution for the data and background for the QCD control region for the 2018 dataset (middle). The expected sensitivity of the full Run 2 analysis compared with the extrapolation of the previous result (using 2016 dataset) to full Run 2 luminosity (right). [Pinna & Shang]

2.4.4 Current Research: Strongly Interacting Massive Particle Search

Scientist Isabelle de Bruyn (Advisor Herndon) completed a search for dark matter in the form of strongly interacting massive particles[44]. This analysis explores the possibility that dark matter is indeed produced at the LHC, and that the interaction cross section with normal matter is so high that the particles are no longer WIMPs, but become so-called SIMPs, strongly-interacting massive particles, being copiously produced at the LHC and leaving observable signals in the detector. Such SIMPs will manifest themselves in the detector as jets in the calorimeter, but with no tracks from charged hadrons. The analysis probes for the first time a unique phase space and is the first search for trackless jets in CMS.

2.4.5 Current Research: Search for Long Lived Particles

Graduate student Abigail Warden (Advisor Black) is searching for evidence of long lived particles looking for displaced vertices. The search relies on a single lepton trigger. The search is then bench-marked looking for long lived stop particles where a stop pairs are produced, travels up to 100 mm, and then decay into a lepton and quark. The analysis searches for dijet events with at least one high p_T lepton and a displaced vertex, where a jet and lepton originate from. The analysis is currently being optimized by Warden to include a dilepton selection and to prepare efficiency scale factors for tracks with large displacements.

2.4.6 Current Research: Dark matter searches with exotic baryons

Graduate student Wren Vettens (Advisor Black) is searching for a hypothetical exotic bound state, known as a “Sexaquark” (S), which is a spin-zero uuddss bound state. It is electromagnetically neutral and, if within a mass range of 1860-1890 MeV, stable on a cosmological timescale, which makes it a possible dark matter candidate from within the Standard Model. We search for the production of its antiparticle ($\bar{S}$) in pp collisions at the LHC and its subsequent annihilation with a neutron in the beryllium beampipe of CMS (see Fig. 9 for a schematic of the $\bar{S}$ annihilation pathway to our final state of interest). Final state particles are reconstructed in the tracker and a boosted decision tree is trained on a Monte-Carlo (MC) simulated signal sample for event selection. The largest background is expected to QCD production of $\bar{\Lambda}^0$ and K^0_{short} . The signal is searched for by constructing a boosted decision tree from variables such as the distance between the primary vertex and the interaction vertex, the transverse momentum of the reconstructed $\bar{S}$ candidate, and the angular distance between the decay product. Vettens is working on the finalization of the background estimation and improvements to the BDT and is expected to graduate at the end of 2023 and publish this analysis.

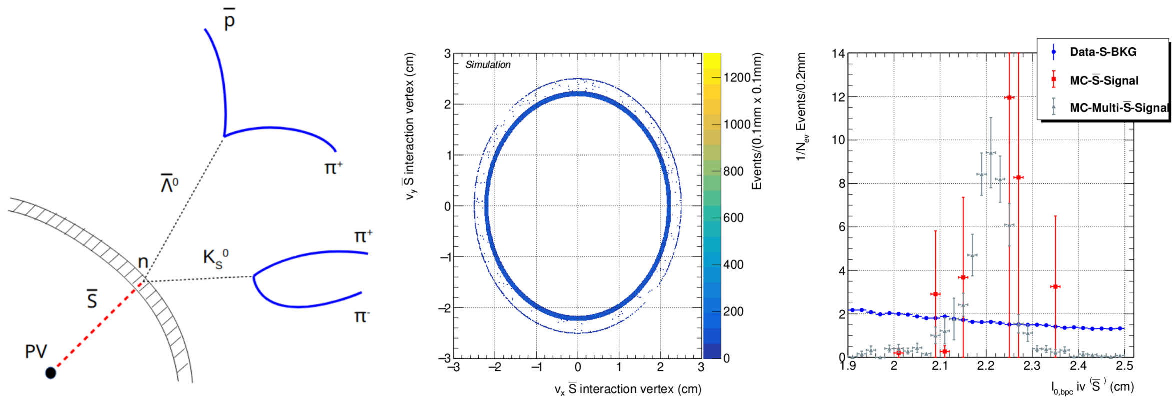

Figure 9: Diagram of the $\bar{S}$ interacting with the beam pipe and subsequent decays (left), location of interaction vertex (center), distance between primary vertex and reconstructed interaction vertex of $\bar{S}$ for signal and background .

2.4.7 Proposed Research: Dark matter searches

While the main-line analyses based on initial state radiation of high p_T jets or photons are planned to be improved with better control of systematic uncertainties, the model dependent searches of mono-Higgs and mono-Z' will be improved with additional Run-3 statistics. Higher statistics available at the HL-LHC will also enable extension of heavy WIMP searches to interesting cosmologically allowed parameter space.

For the top+DM analysis, the plan is to extend the analysis to also explore invisible decays of the Higgs boson using events where the Higgs boson is produced through VH and ttH processes. Motivated by a phenomenology study done by Dr. Pinna [45], another targeted improvement for the overall analysis strategy includes the development of a dedicated top tagger using machine learning techniques for events that fall into the medium boosted regime.

2.5 Searches for new physics with the top quark

The study of the top quark is an important part of the LHC physics program. As the heaviest known elementary particle, the top quark has unique properties and may play a special role in the physics of electroweak symmetry breaking. Studies of rare processes with top quarks help probe the SM in new regions of parameter space and can potentially reveal signs of BSM physics. Additionally, new particles may preferentially decay into final states containing one or multiple top quarks. Searches for dark matter with top quarks has already been discussed in Sec. 2.4.3.

Our group has a long history of searches in this area that have resulted in several publications [46, 47, 48, 49, 50, 51, 52] and theses [David Sperka (Advisor: Bose, PhD 2014), Dylan Rankin (Advisor: Bose: PhD 2018), Clint Richardson (Advisor: Bose, PhD. 2018), Alex Sherman (Advisor: Black, PhD: 2018) and Clare Bernard (Advisor: Black, PhD. 2014).

2.5.1 Current Research: Search for tri-top production

At a center-of-mass energy of 13 TeV triple top quark processes are predicted to have a cross section of about 2 fb, but in BSM scenarios a cross section increase up to a factor of 40 is foreseen. The two Higgs doublet model (2HDM) is one of the simplest and extensively explored models, where the SM particle content is enriched by two (one) CP even (odd) Higgs and a a pair of charged Higgs, that could enhance the cross section of specific processes such as triple top quark production. As demonstrated in Ref. [53], with the LHC data available from Run-2 it is already possible to investigate the existence of BSM physics in triple top quark processes for a large region of the charged Higgs/pseudoscalar mass.

Graduate student Teague (Advisor: Black) and Asst. Scientist Pinna are currently performing a search for triple top quark production using the full Run-2 dataset. This analysis has never been performed before at colliders and could provide strong constraints into the search for charged Higgs in the 2HDM and a first measurement of the triple top quark production in the SM. Our group is responsible for the decay channels corresponding to events containing two same-sign leptons or multi-leptons. To enhance the sensitivity of the search, machine learning techniques are employed in both channels taking advantage of topological differences to separate and identify the small signal (Fig. 10). A publication including a combination with the single lepton channel (being performed by Brown University) is expected in the next year.

2.5.2 Proposed Research: Search for tri-top production

Since triple top quark production is a very rare process, the sensitivity of the analysis will benefit from the additional data available during Run 3. We plan to explore new methods for background estimation for the fake lepton background and will also investigate adding the fully hadronic final state utilizing our Run 2 expertize with other top searches.

2.6 Searches for vector-like leptons

Recent measurements of b hadron decays have shown tensions with the SM that could point to new physics [54, 55]. These tensions could be explained by the existence of vector-like leptons (VLLs). These leptons are referred to as vector-like because they are non-chiral, i.e. their left- and right-handed components have same charge. In particular, VLLs in the context of the "4321 model" [56, 57, 58] could explain existing B physics measurements that are in tension with SM predictions while simultaneously respecting many other measurements that are in agreement with it. A recent search for VLLs in the context of the "4321 model" has been carried out by the CMS collaboration for VLLs decaying to b-hadrons and hadronic tau. The result indicates the possible presence of a signal around 600 GeV at the level of 2.8 standard deviations [59].

2.6.1 Current Research

Motivated by the observed excess, postdoc Koraka (Advisor: Bose) is extending the search for VLLs into the two-lepton and multi-lepton final states (10). For improving the search sensitivity, she is using a data-based technique and her related thesis experience [60] to estimate the overwhelming $t\bar{t}$ background in the 2 lepton final state. New graduate student Elise Chavez (Advisor: Bose) will join this effort upon completion of her training and will help explore the use of Deep Neural Network techniques to enhance the search sensitivity. The analysis framework set up by Koraka uses the Columnar Object Framework For Effective Analysis (coffea), is designed to scale effectively with the Run 3 and HL-LHC datasets, and will leverage Chavez's ongoing work with the Fermilab Elastic Analysis Facility (see Sec. 5.0.1).

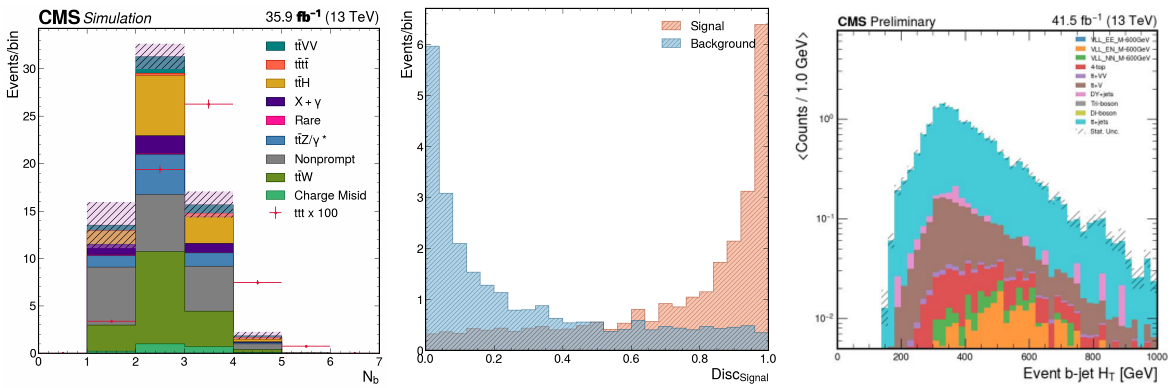

Figure 10: Triple-top analysis: B-jet multiplicity for the signal and background for the triple-top analysis(left), the output of a multivariate discriminant used for signal and background discrimination (middle); VLL analysis: sum of the p_T of the b-tagged jets for the different signal and background contributions (right). [Teague & Pinna; Koraka]

2.6.2 Proposed Research

Run 3 data will be used by Koraka and Chavez to improve our sensitivity to VLLs in the two-leptonic and multi-leptonic final states and also explore different phase spaces allowed by the "4321 model". Asst. Scientist Pinna plans to investigate the associated production of one charged and one neutral VLL with sub-sequential decays into top quarks, bottom quarks and missing transverse energy. She will be joined in this effort by new graduate student Trevor Nelson (Advisor: Bose) upon completion of his training. The expertise acquired by Pinna in final states with heavy quarks and missing transverse energy will be leveraged for this new effort. As a baseline, the three top framework and expertise can be used to develop efficient strategies to improve the sensitivity to VLLs in final states with three top quarks, one bottom quark, and neutrinos. This will be the first result looking for top quark decays of VLLs in the context of the promising "4321 model".

2.6.3 Searches for new physics with the b-quark

Current Research: Lepton flavor Universality measurements in B hadron decays: Post-doc Galloni (Advisor: Black) is testing flavor universality in B hadron decays. Decays of hadrons containing b quarks provide a powerful probe for examining the SM and one of its main principles, lepton universality, and for searching for effects of physics beyond the SM. Semileptonic decays especially, where the B-hadrons decay to another hadron, a lepton, and a neutrino, happen in the SM via tree-level processes and are an ideal setting for testing the universality of the couplings of the three charged leptons in the electroweak interactions. Recently, results from different experiments reported discrepancies with respect to the SM expectations. In particular, measurements of the parameters R(D) and R(D*) corresponding to the ratios of branching fractions of the B meson with leptonic decays in the μ and τ channels BABAR [61] , Belle [62] and LHCb [63] show disagreement with SM predictions. A similar analysis is performed by the CMS experiment. Galloni is leading the measurement of the cross-section in the τ channel in the decay mode of the B meson to a neutrino and three charged pions. A data driven approach was used for the background estimation

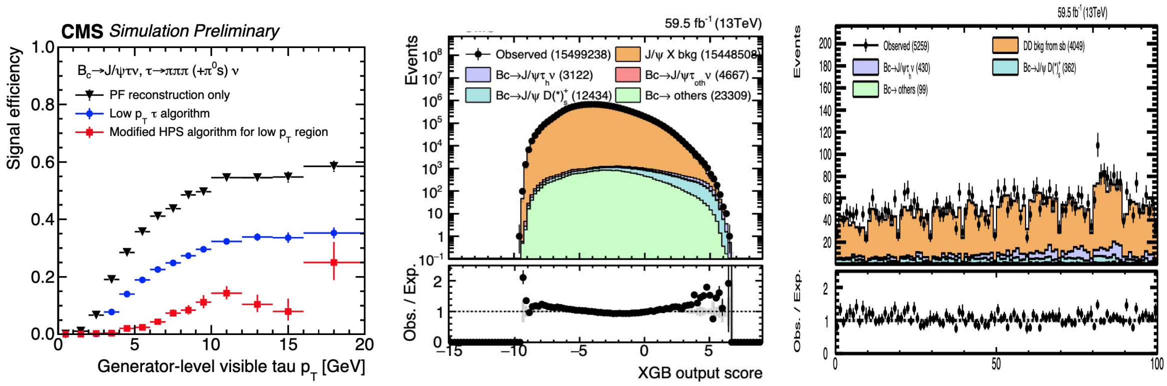

Figure 11: Tau identification efficiency as a function of p_T at the same misidentification rate(left). Multivariate output for signal selection of B meson decays and backgrounds (middle). Distribution of 2018 signal enriched data region of the expected signal and background events in the unrolled two dimensional $\rho_1 - \rho_2$ mass distribution(right) .

and a signal discriminant formed from the $\rho \to \pi^+\pi^-$ from the τ decay along with angular variables that help separate the signal and background. The analysis is now in collaboration review and is expected to be finalized and released in 2023.

Current Research: Low Pt tau identification:: Postdoc Galloni (Advisor: Black) is one of the main developers of a new algorithm for the reconstruction of low pT hadronic τ lepton decays. Galloni (Advisor: Black) served as co-convener of the Tau identification group within the Tau physics object group from September 2017 to September 2019. Under Galloni's leadership, a new deep neural network-based tau identification algorithm (DeepTau) was developed, ameliorating the performance of τ identification efficiency substantially as shown in Fig. 11: at the same level of efficiency for genuine hadronic τ decays, the mis-identification probabilities for QCD jets, electrons, and muons decrease by at least a factor 2, 3, and 4, respectively.

2.7 Future Colliders Work

The UW group played a significant role in the Snowmass 2021 energy frontier group. Prof. Bose co-led the EF09 subgroup that studied general BSM explorations [64]. Prof. Black co-led the muon collider forum. Prof. Dasu co-led the electron-positron collider forum. The energy frontier report [65] concluded that Cool Copper Collider Higgs Factory and the 10-TeV/10-fb^{-1} Muon Collider are both of interest, especially in the context of early start and US siting.

The group has submitted white papers to the Snowmass process [66, 67, 68]. Graduate student Lomte (Advisor: Dasu) evaluated the effect of beam-induced-background on the muon-collider b-pair invariant mass peak. UG student Jia (Advisor: Dasu) obtained the significance for measurement of SM dihiggs production for various centers of mass energies and luminosities of the muon collider. Thorough exploration of heavy WIMPs in electroweak multiplets, mediated by the Z-boson, will require a 10-TeV or higher scale with 10s of ab^{-1} data. Asst. Scientists Pinna and Sharma along with the UG students Nikhilesh Venkatasubramanian and Chen looked at electroweak multiplet WIMP candidate reach at a muon collider. Figure 12 summarizes some of this work. UG student Mettner and Nee (Supervisor: Mohammadi) are evaluating beam backgrounds at the C3.

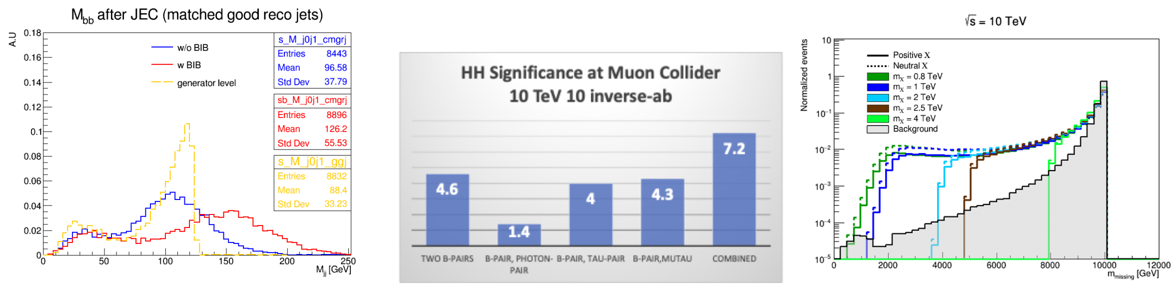

Figure 12: Effect of beam induced background (Lomte) at Muon Collider on dijet mass distribution from full simulation (left). Signal significance for HH production (Jia) using simple cut-and-count Delphes analysis (middle). Distributions of missing mass (Venkatasubramanian) from various masses of dark matter candidates in Delphes analysis (right).

2.8 Physics Analyses Service

Profs. Black, Bose, Dasu, and Herndon, and Scientists Savin, Everaerts, Pinna, Sharma, emeritus Scientist Loveless, continue to participate in many CMS physics analysis review committees (ARCs), which scrutinize both the analysis methodology for accuracy and ensure publishable papers. Dr. Loveless chairs CMS SM physics publication committee. Prof. Herndon performs the job of organizing Wisconsin review for papers assigned for our Institutional Review in the publication process.

2.9 Fermilab LPC Activities

Prof. Black is the current LPC co-coordinator playing the important role of bringing the US CMS LHC community collaborating together based at the Fermilab. Asst. Sci. Pinna and Prof. Dasu are LPC Distinguished Fellows. The faculty and students based at Wisconsin take part in Fermilab LPC activities regularly. The junior students have participated in the CMS Data Analysis School, HATS@LPC and other workshops to learn about CMS, its software and analysis techniques. Senior students and postdocs have organized and led tutorials for CMSDAS. The faculty have lectured on CMS physics and trigger at such schools several times. Prof. Herndon has a strong collaboration with the SMP team at the LPC and has in the past taught a workshop course on tracking and large-scale reconstruction software development while on leave at Fermilab. Prof. Dasu has organized several LPC events, collaborates with LPC scientists on trigger projects and has served on the LPC management board. Prof. Bose has served on several LPC committees including the LPC management board and collaborates with LPC scientists on physics analyses and software and computing projects.

3 CMS Trigger Activity

3.1 Trigger Overview and Responsibilities

For the original LHC design luminosity of 10^{34} cm^{-2} s^{-1}, 25 inelastic collisions on average occur at each beam crossing with a frequency of 40 MHz. This input rate of 10^9 interactions every second is reduced by a factor of 10^6 to 1 kHz, the maximum rate that can be archived by the on-line computer farm. CMS reduces this rate in two steps. For the Level-1 Trigger (L1T) all data is stored for 4 μs, after which no more than 100 kHz of the stored events are forwarded to the High-Level Triggers

(HLT). The L1T system (See Figure 13 uses custom electronics to identify, find the position of and sort in importance physics objects such as electrons, muons, jets, and taus as well as the sum of missing energy. Phase-1 trigger upgrades, in place since 2015, are operating at a factor two above the instantaneous design luminosity of the LHC, while the CMS L1T rate remains limited to 100 kHz by the readout electronics. Wisconsin group has been responsible for design, construction, upgrades and operation of significant portions of the CMS L1T systems from the very inception.

In addition to the current L1T and HLT operations, the significant futuristic efforts of the group are: (1) Upgrade of the L1T for the HL-LHC [69] (2) Planning and execution of HL-LHC HLT algorithm and technical improvements with GPUs.

Prof. Smith, considered the architect of the CMS Trigger System, as recognized by his APS Panofsky Award, was the leader of the successful UW trigger group. Prof. Dasu, who was responsible for the design and simulation of the original and the phase-1 L1 calorimeter trigger systems serves as the US-CMS Level-3 Manager for the Calorimeter Trigger Upgrade. Prof. Dasu served as the original online selection group convener, which designed and implemented the original HLT system for CMS based on the standard offline software. He continues to advise the trigger studies group that operates this system. Prof. Bose had served as the CMS Trigger Coordinator. Prof. Bose's focus was on HLT system and its physics performance. Currently, her emphasis is in optimizing the HLT operations with GPUs and output data volumes, with physics priorities in mind.

UW Senior Scientist Savin is co-leader responsible for the operations of the L1T Calorimeter Trigger (CT). For the HL-LHC period Savin is CMS co-manager of the stand-alone calorimeter trigger system. In the past, Dr. Savin was responsible for the trigger data quality management both for L1 and HLT systems, serving as Level-2 manager in the trigger studies group. Asst. Sci. Sharma completed his role as the L1T Technical Co-coordinator recently. Both Savin and Sharma are supported by the US CMS project at 25%-level in recognition of their important roles in L1T operations and upgrades.

3.2 Run-3 Calorimeter Trigger System

The μTCA based Phase 1 upgrade to the L1T, which is fully operational since 2016, built out of Field Programmable Gate Array (FPGA) and multi-gigabit optical transceivers includes the Wisconsin contribution to L1T (See Figure 13). Working with Profs. Smith and Dasu, the Calorimeter Trigger Processor card (CTP7) was designed by UW Electronics Engineer Tom Gorski with Firmware provided by UW Engineers Ales Svetek and Marcelo Vicente (US CMS Project Supported) to implement the Layer-1 of the Phase-1 CT. The CTP7 uses a Virtex-7 FPGA as its primary data processor. Additionally, this card design is the first in CMS to employ the ZYNQ System-on-Chip (SoC) running embedded Linux to provide TCP/IP communication and board support functions. The multi-gigabit (up to 10 Gb/s) input/output on optical fibers are located on the front side of the CTP7. Multi-gigabit inputs and outputs are also located on a custom µTCA backplane built by Vadatech to UW engineered specifications to allow data sharing.

The UW group has been responsible for maintenance and operation of the L1T system, with special responsibility for the calorimeter L1T subsystem. Asst. Sci. Sharma served as the L1T technical coordinator. The graduate students Mallampalli, Shang and Tsoi work with Senior Sci. Savin and Sharma onsite providing on-call service, calibrations, and making any necessary software updates. We review the trigger performance daily to ensure it is working correctly and properly calibrated. We maintain and update lists of bad channels (either dead or mis-calibrated). We also diagnose and repair electronics modules, cables, power supplies and system components. Since the trigger is a critical item for CMS during running, at least one UW expert is on call 24 hours a day.

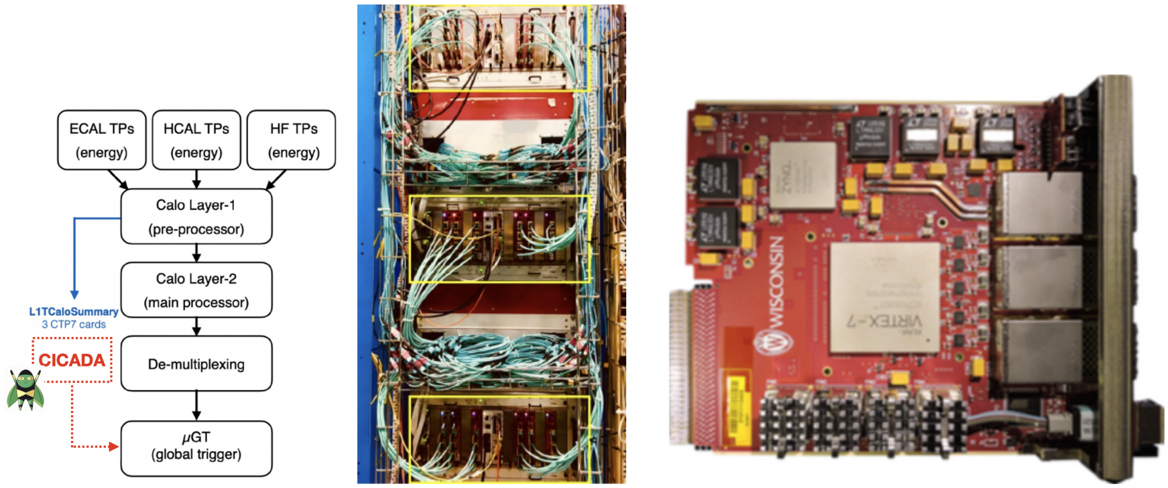

Figure 13: L1T calorimeter trigger system with the new CICADA addition (left). Layer-1 installation in Point 5 with three uTCA crates with CTP7s (middle). CTP7 Board (right)

During the long shutdown that just completed, Wisconsin, Princeton and Hyderabad groups worked together to build new capabilities based on machine learning for across-the-board improvement and dedicated algorithms for boosted jet and τ topologies. Anticipated improvements in performance of the trigger system with these additions are shown in Figure 14.

With an additional set of Wisconsin built CTP7 μTCA cards in each crate and taking advantage of the backplane links connecting the cards, and an upgrade of the firmware based on HLS4ML, we have built additional capabilities for Run-3. The L1T boosted jets and taus provide increased acceptance for several Higgs processes. The ML algorithm employs Calorimeter Image Convolutional Anomaly Detection Algorithm (CICADA), which provides a model-agnostic trigger for new physics, removing bias towards any particular physics model. The ML algorithm's large resource utilization is mitigated using Knowledge Distillation and Weights Quantization techniques and then implement on FPGAs with HLS4ML software package. The hardware and core firmware additions are supported by the project supported personnel and Asst. Sci. Sharma. Graduate student Tsoi (Advisor: Dasu) did the algorithm firmware development with the Princeton group.

3.3 HL-LHC Trigger System

For the HL-LHC running, planned to start in 2027, the luminosity is planned to exceed 5×10^{34} cm^{-2} s^{-1}, while the electroweak physics goals, thereby the trigger thresholds remain in place. Further the pileup increases significantly. These complications necessitate a complete overhaul of the CMS architecture to use tracking in the L1T for the first time, with a L1T rate up to 750 kHz, HLT rate up to 7.5 kHz and a totally new trigger system [69]. The overhauled trigger system block diagram is shown in the Figure 15. The experienced UW electronics engineering team led by Tom Gorski, includes firmware developers Ales Svetek, Kiran Das and software engineer Jesra Tikalsky, all supported by the US CMS HL-LHC project funded by the DOE, are charged with building the ATCA based electronics boards and the core firmware and software, for the calorimeter, track-only and correlator (implements particle flow ideas correlating calorimeter clusters with tracks) trigger systems. Our DOE supported group is responsible for delivering the complete 35-board calorimeter trigger, 50% of the global track trigger (6-boards) and 50% of the correlator trigger (36 boards). The Wisconsin-Princeton-Hyderabad physicist group is co-led by Scientist Savin in

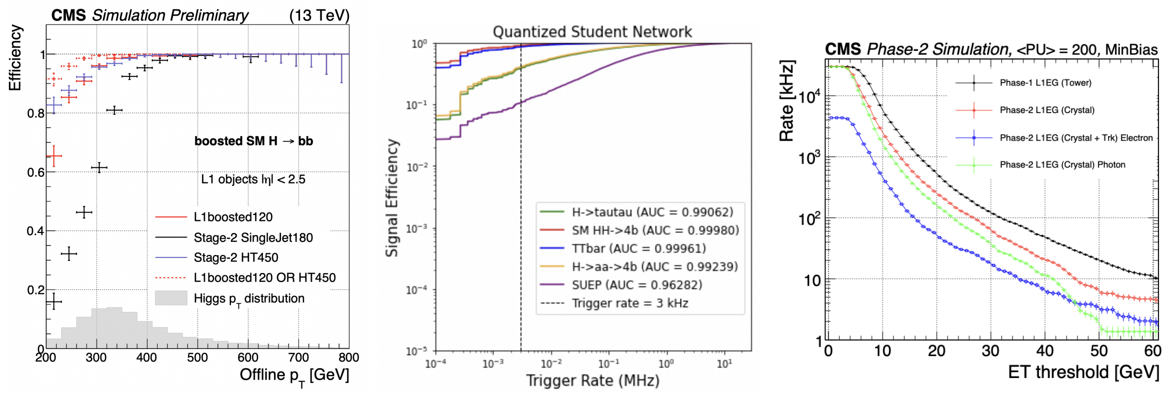

Figure 14: Improved Run-3 L1 boosted jet trigger performance for a nominal 2 kHz background rate (left). Improved Run-3 L1 ML-based "anomaly detection" trigger performance for a variety of signals as a function of rate (middle) Improvement in rate reduction for electron and photon triggers using crystal data and L1 tracks in HL-LHC trigger (right).

the CMS trigger management team. Savin and this group are in charge of the calorimeter trigger algorithmic firmware, which produces standalone calorimeter-based triggers for electron/photon (performance shown in Figure 14), τ_{had}, jets and MET/MHT/HT sums. This subsystem also makes and transmits energy clusters for their correlation with the L1T tracks to form particle flow objects. Prof. Dasu is the US CMS Control Account Manager for the calorimeter trigger system, reporting to Fermilab US HL-LHC project management team.

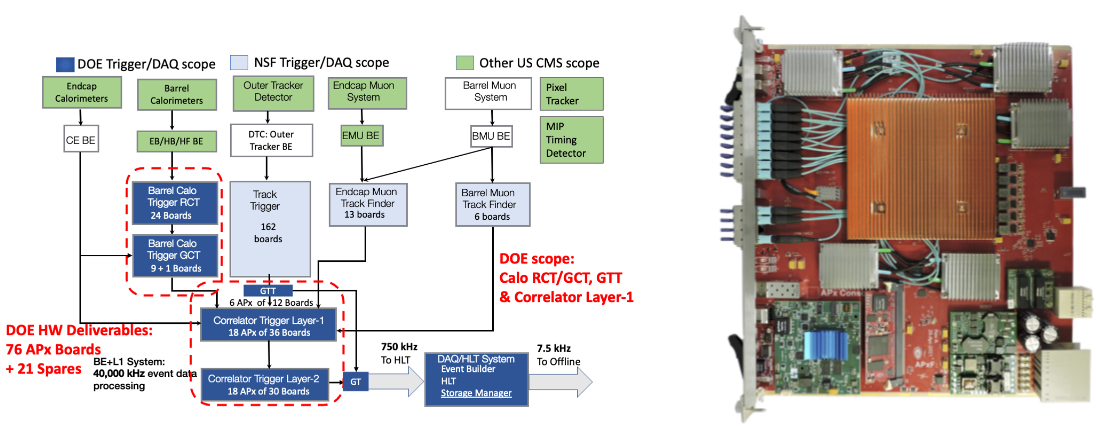

Figure 15: The HL-LHC Trigger System showing the UW hardware responsibility (left). The APxF ATCA board built by the UW group (right).

The Advanced Processor (APx) general purpose ATCA (Advanced Telecommunications Architecture) boards with high-end FPGA (Xilinx VU9P or VU13P) processors and over a hundred 25-Gbps optical links, using Samtec opto-electronics are built by the UW team. The board features mezzanines for embedded linux (e.g. ZYNQ) and card environment monitoring and control (IPMC). The APxF board, shown in Figure 15, has been tested extensively and is proving to be suitable for all planned trigger applications. Two generations of APx boards are working as designed have been integrated in to test platforms at Madison, CERN, FNAL and Colorado. The team also developed core firmware that sports a sandbox for algorithm implementation. The core firmware handles all communication between cards implementing CMS standard trigger protocols (CSP) developed and implemented by the UW team. Both calorimeter and correlator physics teams build trigger algorithm blocks that operate within the sandbox to make functional systems. Testing of the initial firmware blocks has begun. Further, the AP-platform is also serving as a model for backend electronics board for the calorimeter, which are built by NSF-supported collaborators at Notre Dame.

Under the leadership of Senior Scientist Savin, Asst. Sci. Sharma and students Mallampalli, Shang and Tsoi are working on the HL-LHC Calorimeter Trigger Upgrade. They have produced several C++-based trigger software algorithm modules, which are synthesized using Xilinx Vivado HLS in to firmware blocks. They are also integrating those algorithmic firmware blocks with the core firmware produced by the UW engineering team to produce "bitfiles" for regional (RCT) and global calorimeter trigger sub-systems. They are currently testing full slices of the system by using multi-module test setups operated by the UW group. Continued support for the group is necessary to provide this important component of the CMS trigger for the HL-LHC.

3.4 High Level Trigger

Our group has played a leading role in CMS High Level Trigger (HLT) development and operations since the start of Run 1. Prof. Bose served as the Deputy Trigger Coordinator (2011-2012) and as the CMS Trigger Co-coordinator (2014-2016) and Scientist Pinna served as the L2-convener of the STEAM (Strategy, Trigger Evolution & Monitoring) group (2020-2021) within the Trigger Studies Group (TSG). As convener of the STEAM group, Dr. Pinna was responsible for working together with all the physics groups to develop trigger menus for CMS and to monitor their performance (rates, timing, efficiencies etc.). She played a very active role in lowering the bar for trigger studies for the physics groups and engaged more people in this effort by organizing a number of tutorials over the last couple of years [e.g. Trigger Hands-On Advanced TutorialS (HATS) 2021, and the Trigger exercise during the CMS DAS (2022, 2023)]. Her leadership of the STEAM group was instrumental in preparing trigger menus for Run 3 data taking.

3.4.1 HLT Algorithm Development and Performance Studies

Our group members have traditionally made strong contributions to HLT algorithm development and performance studies. Former graduate student Dylan Rankin (Advisor: Bose) spearheaded the effort for implementing jet substructure techniques at the HLT for identifying boosted top quarks and W bosons while former graduate student Clint Richardson (Advisor: Bose) held the responsibility for evaluating and monitoring the CPU performance of all HLT algorithms. Student Parida has continued this tradition and is playing an important role in performing rate measurements for Run 3 trigger menus. For Run 3, CMS made a big change and added Graphical Processing Units (GPUs) to the HLT farm. This change was a major upgrade requiring significant changes to our code base with many algorithms being offloaded to GPUs. Parida has played an important role in the commissioning effort and regularly performed detailed studies of CPU and GPU trigger performance by evaluating trigger rates and using event-by-event comparisons. His work before the start of Run 3 was key in identifying several issues related to the new GPU code that have since then been fixed leading to smooth data-taking.

Postdoc Koraka (Advisor: Bose) serves as the TOP PAG trigger convener and is responsible for monitoring the group's trigger paths and ensures that the group's trigger needs are covered. She communicates with both analysts and trigger coordination and ensures that all needed paths are integrated in the trigger menu and suggests changes or addition of new paths that will improve the group's physics reach. Additionally, during data-taking periods, she oversees weekly monitoring of the data, trigger efficiency measurements and additional performance studies to ensure high data quality and to facilitate early spotting of any potential issues. Koraka is also responsible for the review of analyses under the TOP PAG and checks for correct usage of trigger paths, trigger efficiency and scale factor measurements.

3.4.2 HLT Operations

Group members have made several important contributions to trigger operations over the years. Former postdoc Aram Avetisyan served as the co-convener of the Field Operations Group (FOG) within the Trigger Coordination area (2013-2015) and former graduate students Clint Richardson (Advisor: Bose, PhD. 2018) and Dylan Rankin (Advisor: Bose, PhD. 2018) were members of the Field Operations Group and served as HLT on-call experts. Graduate student Parida has trained to become an HLT Detector-On-Call (DOC) expert and is part of a small team of CMS-wide experts providing immediate 24/7 support for any HLT issue related to operations.

3.4.3 HLT Plans for Run 3 and beyond

Scientist Pinna together with graduate student Parida (Advisor: Bose) will work on trigger menu preparations for Run 3. Currently discussions are ongoing regarding the 2023 LHC run during which the LHC may deliver record instantaneous luminosities over $2.4 \times 10^34 cm^{-2} s^{-1}$. The high luminosity and pileup of around 70 will have an adverse impact on the total rates and increased running at high average pileup may degrade the performance of many trigger algorithms. Parida will work on evaluating trigger rates for a variety of scenarios including threshold changes. He will continue to study and validate GPU versions of new HLT code and serve as an HLT DOC.

Postdoc Koraka and new graduate student Nelson (Advisor: Bose) will work on porting the E/gamma reconstruction to run on GPUs. In particular, they will work on the electron seeding algorithm that contributes most to the total E/gamma reconstruction time. This work has synergy with our effort in the software and computing (S&C) area and takes advantage of the GPU resources at our Tier-2 and also the Center for High Throughput Computing (CHTC) at UW.

Scientist Pinna plans on exploring the implementation of fast, online calibrations using ML techniques. In many searches, in particular DM analyses, the sensitivity of the analysis is limited by the threshold imposed on the missing transverse energy. The threshold has to be kept low enough to allow the sensitivity to mediator masses below 100 GeV but at the same time has to be kept high enough not to exceed the rate L1/HLT rate constraints. In addition, due to different performances in data and simulation, at the analysis level the minimum selection on MET has to be further increased with respect to the trigger threshold value. Online calibrations implemented using ML techniques could ensure prompt, accurate, and uniform performance through the different data-taking conditions. Pinna plans to take advantage of Run 3 that offers a unique possibility to develop and train the ML models which then can be used as default for HL-LHC. Leveraging our HL-LHC L1 trigger and S&C expertise, our group also plans to participate in HLT algorithm and menu development for the HL-LHC.

4 Muon System Activities

4.1 Cathode Strip Chamber System

The UW role in the CMS Muon system project includes leadership in the Cathode Strip Chamber (CSC) forward muon system and responsibilities for chamber construction, refurbishment, integration, commissioning, operations, monitoring, and performance analysis. In addition, the UW group is involved in HL-LHC R&D on chamber longevity and operational modifications. UW Senior Scientist Dr. Lanaro was the CMS Project Manager for the CSC system from Sept. 2015 through Sept. 2019, served as the US CMS Deputy EMU L2 Project Manager and led efforts in HL-LHC R&D on chamber longevity until his retirement in 2021. Assistant Scientist De Bruyn serves as CSC radiation protection officer, CSC run coordinator and full Muon system Upgrade coordinator. Previously Dr. De Bruyn served as deputy and then primary coordinator of the CSC upgrade. Prof. Herndon leads the UW CSC program, supervising scientist De Bruyn, graduate students He, Mondal, and Trembath-Reichert (Masters degree 2020), and for the period of long shutdown 2 (LS2) Sreekala (Advisor Dasu) and Vetens (Advisor Black). Prof. Herndon also serves as CSC resource manager and the CSC representative on the muon conference and publication committee.

4.1.1 LS2 CSC Consolidation and Upgrade for the HL-LHC

As part of the Phase-II HL-LHC upgrade, the CSC detectors were upgraded to cope with the Level 1 trigger latency (12.5 μs) and rate (750 kHz). The readout electronics and front-end DAQ of the most forward 108 CSCs were upgraded as was done in LS1 for ME1/1 chambers. The refurbishment of the on-chamber electronics commenced in early 2019 at the beginning of LS2 and was completed in early 2021 nearly on schedule despite the difficulties of the Covid epidemic. The UW team at CERN worked on chamber removal, refurbishment, testing, installation and re-commissioning. Dr. Lanaro and Dr. De Bruyn primarily worked on chamber removal as well participate all aspects of the project providing leadership and expertise. They also designed work packages to safely implement Covid related restrictions. Dr. De Bruyn serves as radiation protection officer assessing the radiation conditions of the worksite and system components, responsible for designing and implementing radiation safety procedures. In addition, she served as deputy and then lead CSC upgrade manager during the critical period of completing and installing the front-end electronics upgrade. Graduate students Sreekala, Trembath-Reichert and He worked on the extraction, refurbishment and testing teams respectively. The UW group is responsible for multiple infrastructure projects associated with the upgrade including low voltage distribution, chamber covers, thermal pads and cooling circuits. The former items were designed and fabricated at the UW Physical Sciences Laboratory under the direction of Prof. Herndon and the low voltage distribution boxes were assembled and installed by graduate student Trembath-Reichert. In Run 2 several CSC cooling circuits exhibited leaks. To address this a long term robust solution was designed under the direction of Dr. Lanaro and were installed on ME1/1 chambers during LS2. With the completion of the electronics upgrade Dr. De Bruyn moved to the position of operations manager for the CSC responsible for the commissioning of the CSC detector.

4.1.2 Run 3 Commissioning and Data taking

Following the successful phase-II upgrade of the CSC on detector electronics and the recommissioning of the CSC detector, both led by Dr. De Bruyn, CMS entered the Run 3 data taking period. During the first year of Run 3, Dr. De Bruyn, as CSC operations manager, had operational responsibility for the CSC detector with the task of maintaining stable and efficient operation of the CSC system. Detector On-Call (DOC) experts are key people ensuring the successful operation. Graduate students and He and Mondal served as DOCs, responsible for maintaining the system (online software, detector hardware and electronics, system infrastructure and services) in a healthy state and for fast response and action in case of unexpected issues.

4.1.3 Offline CSC Performance studies

Supervised by Prof. Herndon the UW CSC group continued its institutional responsibility for the monitoring of the performance of the CSC system. Detector performance studies are focused on using tag and probe type studies of Z decays to muons to understand hit and segment reconstruction and trigger primitive (LCT) efficiencies. During his sabbatical period in the fall of 2021 Prof. Herndon redesigned the T&P to enable reprocessing of the full T&P ntuple data, typically tens of millions of Z candidate events, on times scales of 30 minutes in order to enable complex studies on short time scales. The new software was tested by graduate student Mondal by performing a study inefficiencies due to high voltage problems in the Run 2 data. Using the new T&P analysis code the UW group was able to produce a full analysis of the CSC segment reconstruction and LCT efficiencies within 2 weeks of the start of Run 3 data taking, limited by the time to collect sufficient Z data. The new software enables high granularity studies of system performance that can identify the effect on efficiency of full or partial failures of individual readout components for the strips ((D)CFEBs), wires, high voltage segments, and as function of time [16] [17]. In addition, new software was used to provide fast feedback to make operational changes in the readout configuration providing new efficiency data on the time scale of days or a maximum of one week, only limited by the CMS experiments prompt data processing time. This was, for instance, used to test and choose between various readout timing configurations to address an OOS (out of sync) readout issue in the ME1X rings. Muon reconstruction efficiency, trigger efficiency, detector time and space resolution have been stable throughout Run 3 and generally as high quality as during Run 2 despite the replacement of the readout electronics in the majority of the CSC rings (for instance see [70] page 17 for a comparison to Run 2 performance).

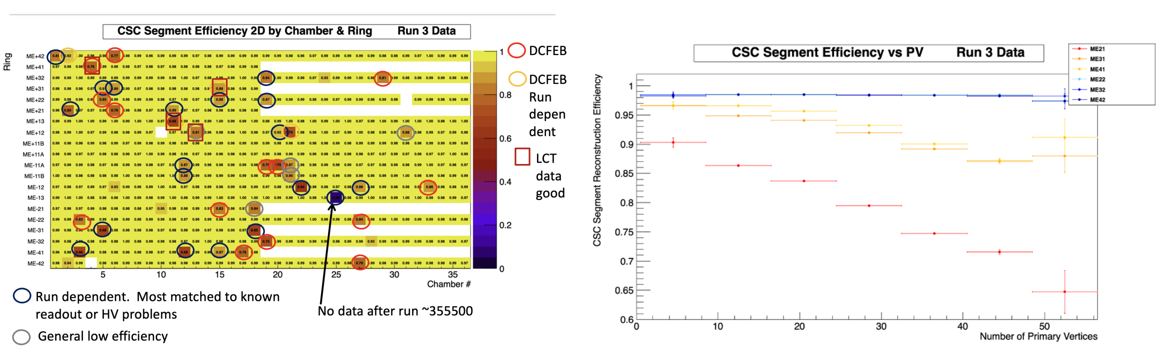

Figure 16: Evaluation of efficiency in early 2022 CSC data with most issues classified (left). OOS ME1X efficiency problem is exacerbated by high luminosity as seen in distribution of efficiency vs the number of primary vertices(right)

4.1.4 Other CSC activities

Prof. Herndon serves as CSC representative on the muon conference and publication committee. He is responsible for providing opportunities for postdocs and students to present their work at conferences and for reviewing talks and proceedings to ensure high quality. Prof. Herndon also serves and CSC resource manager responsible for manpower and budgets for the international CSC collaboration. During the period of 2021 and 2022 this has involved substantial planning to manage the expected impact of the decline or secession of Russian Federation involvement at CERN and the inability of the RF to complete products due to lack of funding, export restrictions on advanced

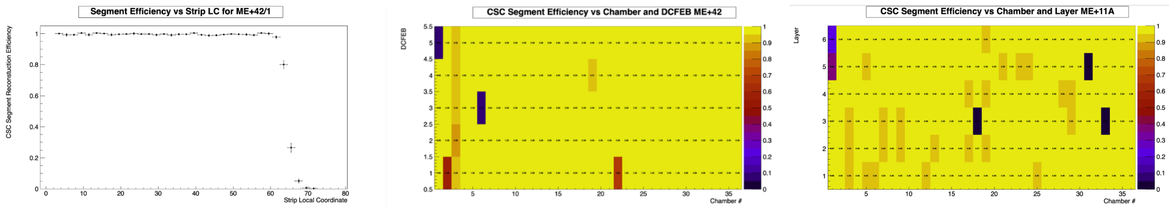

Figure 17: DCFEBs readout 1/5 of the strips in a CSC chamber. The fifth DCFEB is found to be faulty in this chamber(left). An efficiency plot for locating failed DCFEBs in a CSC ring(middle). HV is distributed by layer in the ME11 chambers. Five HV segments has failed in chamber layers in this ME11 ring(right).

electronics and the eventual end to RF-CERN collaborations. An additional project involving HL-LHC R&D on chamber longevity was conducted by graduate student Vetens (Advisor: Black).

4.1.5 Summary and Future activities

In summary, the UW group will play a major role in maintaining the highest CSC detector efficiencies and recording high quality data to be used in physics analyses throughout the lifetime of the experiment and will train the next-generation UW students and post-docs in the UW institutional responsibilities: detector operation, detector infrastructure, LV power distribution, on-call detector experts, data quality monitoring and detector physics performance studies. For instance to enhance our effort toward the last goal, with his new graduate student, Justin Marquez, Prof. Herndon intends the implement a new processing data flow that utilizes express CMS processing in order to enable one to two day turnaround of performance evaluations which also is the minimum amount of data needed for reasonable granularity studies of system performance at high luminosity in order to provide feed back for operational decisions. This software could be implemented within the DQM data flow of the muon system and also to generate separate standalone ntuples that allow for flexibility in studies. In addition, Dr. Bruyn now serves as overall Muon system upgrade manager providing leadership for the completion of the phase-II upgrade of the muon system including production of components for the CSC back-end readout and the new detectors for the RPCs and GEMs.

4.1.6 Synergistic activities with GEM

The UW group intends to leverage experience gained in the GEM electronics and detector operation along with existing expertise on CSC performance monitoring to design integrated monitoring across the combined CSC and GEM detectors. As these two sets of detectors will provide the primary measurements used to determine transverse momentum for muons in the endcap region, integrated monitoring is essential for guaranteeing the performance of the upgraded EMU system.

4.2 Gas Electron Multiplier Chamber Upgrade

Since joining the UW, Prof. Black is leveraging his ATLAS L0MDT experience in a similar HL-LHC upgrade project for the CMS GEM system. Gas Electron Multiplier (GEM) detectors were installed during the second-long shutdown in the end-cap muon system of CMS. Additional layers will be installed in preparation for HL-LHC running. The GEM detectors will add redundancy to the muon system in the $1.6 < |\eta| < 2.1$ region where the end-cap muon system had the fewest number of layers but the highest background rate. In addition, the GEM detectors will increase the acceptance of the system out to $|\eta| < 2.9$ and improve the triggering capability of the endcap muon trigger by instrumenting the region with the highest magnetic field. The US scope in the GEM project is a large fraction of the readout electronics and the addition of the GEM detector information to the hardware trigger. Prof. Black was appointed the US L3 coordinator of the GEM HL-LHC electronics upgrade in August of 2018. The US scope of the project includes approximately half of the readout electronics focusing on the back-end electronics. Since 2020 Prof Black had been the GEM project electronics coordinator for international CMS. Additionally, Prof. Black was appointed as the GEM review coordinator for all GEM activities in international CMS.

The scope of the US project includes the optical hybrid (OH) boards which collect and process data from the front-end ASICs (VFATs), the optical links, and the ATCA back-end card which then sends the data to the endcap muon trigger finder and DAQ path. Additionally, the OH boards send the data to the CSC trigger processor. The UW group (Prof. Black) is responsible for the GEM electronics integration and commissioning of the GEM electronics, and work on the development and implementation of the stub-finding algorithm for the ME0 detector. Since 2020, UW Scientist Everaerts (Advisor: Black, supported by upgrade and operations) has lead the integration effort at CERN testing the electronics on the CERN test stand and the GE 2/1 demonstrator already installed and currently holds the position of L3 integration manager. Dr. Everaerts has also setup with UW students Warden and Aravind (Advisor Black) the ME0 detector and electronics stack and test stand evaluating noise, discharge rate, and developing software and firmware to evaluate the chamber performance shown in Fig: 18 and published in [71].

4.2.1 GEM Operations

Postdoc Galloni (Advisor: Black) and the and graduate students Vetens (Advisor: Black) and Teague (Advisor: Black) joined the GEM project focusing on developing the software for the readout and the calibration of the electronics of the GEM detector. Prof. Black was CMS Deputy GEM Run and Commissioning coordinator between 2019-2020 and worked to organize and oversee the commissioning of the GEM detectors and operations. From 2021 to present Postdoc Galloni has been the GEM Run coordinator. During data taking, making sure that the proper settings for the electronics are used is of critical importance and students Warden and Aravind participated in the commissioning and operations activities with weekly detector and on call shifts for the GEMs. Postdoc Galloni is the main developer of the GEM Calibration suite. Another central feature that the PhD Student Teague (Advisor: Black) is working on is the amelioration of the monitoring software tool that is of crucial importance while taking data, to ensure that the hardware and the software are fully functional. Data formatting status (errors, event counters, etc.), system buffer status, and link status will also be monitored, as they all provide key information in the case of system malfunction. Dr Galloni is leading the GEM DAQ operations group responsible for integration of the electronics and xDAQ software development and operations. Prof. Black, Galloni, Vettens, and Teague are testing the electronics of the GE1/1 detector where a external drain resistor was inserted as protection from discharges for the VFAT3 in series with an input protection circuit. Recently other protection circuits have been proposed, where the drain resistor is paired with a de-coupling capacitor or a diode and are currently under study. Two kinds of study are being performed: on a GE1/1 chamber a test stand was prepared to study the damage protection efficiency of the different proposed circuit. By creating discharges induced by alpha particles from Am241 radioactive decays in the detector under harsh operating conditions; on a GE2/1 chamber the effects of the different protection on the signal are being studied in terms of induced crosstalk, noise, signal efficiency, and possible signal shape distortion.

In 2020 the GEM software was redesigned: in fact from mainly consisting in a collection of routines used for the quality control during production and a prototype for the data taking with a few chambers during the slice test in 2018, the software was restructured to be able to scale to the complete system: a full detector consisting of 144 GE1/1 chambers, with an eye to the future integration of GE2/1 and ME0, ensuring the compatibility with the rest of the Phase-2. Postdoc Galloni and graduate student Teague redesigned the monitoring software tool that is of crucial importance while taking data, to ensure the hardware and software are fully functional. Data formatting status (error, event counters, etc) system buffer status, link status, and possible communications are monitored described in [72].

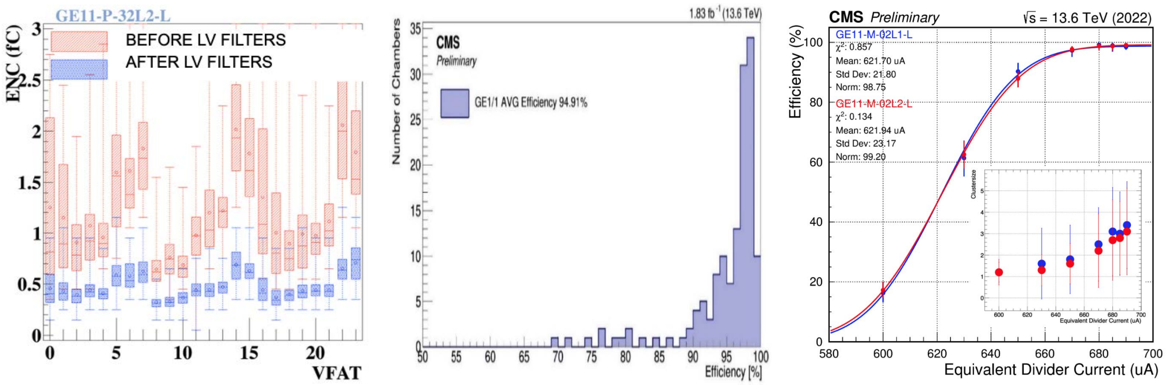

Figure 18: Reduction of noise with low voltage filters installed in different VFATs (left), Efficiency measured in GE/1 detectors during run-3 (center), efficiency as a function of equivalent divider current (as a measure of applied voltage) for GE 1/1 chambers (right).

5 Computing

The UW group operates one of the largest university-based computing facilities for HEP in the country under the supervision of Prof. S. Dasu. This facility was augmented with a large GPU cluster recently. The group also has a leadership role within the USCMS Software and Computing project with Prof. T. Bose serving as the Deputy USCMS Software and Computing (S&C) Operations program manager. This responsibility includes oversight of USCMS facilities (Tier-1, Tier-2s, Tier-3s, networking, cybersecurity), software (including the CMS software framework and data management), operations (contributions to workflows and CMS-wide computing services) and R&D efforts towards software and computing for HL-LHC. In particular, given the budget constraints and the daunting challenge posed by the flood of data expected during the HL-LHC era, Prof. Bose is actively engaged in energizing USCMS R&D efforts for developing the computing and software systems for the HL-LHC. These efforts include, among others, adapting reconstruction algorithms to run on heterogeneous computing resources, data management tasks, and facilitating use of Machine Learning for physics analyses and operational tasks. Prof. Bose spearheaded the development of the "R&D Initiative" program – an annual opportunity for USCMS PIs to get partial support (e.g. half-postdoc) from the Operations program for S&C HL-LHC R&D activities. The projects are PI driven but the priorities are provided by the S&C program leadership and Prof. Bose oversees the selection process. The program has enabled workforce development by incorporating junior effort into the S&C program as well as diversified participation by bringing new individuals and institutes into S&C.

5.1 HL-LHC R&D

Our group is involved in several HL-LHC R&D projects. Postdoc Koraka (Advisor: Bose) together with graduate student Nelson (Advisor: Bose) has started to work on porting part of the electron reconstruction, the electron seeding algorithm, to run on GPUs. The CMS electron reconstruction is performed in modular steps involving several algorithms and takes up approximately 5% of the overall HL-LHC reconstruction time of which the "seeding" step dominates. Seeding is necessary to identify hit patterns in the pixel tracker which are compatible with an electron trajectory. The goal of our group's project is the improvement and acceleration of the current seeding algorithm by adapting it to run on GPUs taking advantage of the massive parallelization they allow. A version of the algorithm could also be deployed in the HLT already in Run 3.

Graduate student Elise Chavez (Advisor: Bose) is working with Fermilab scientists and computing professionals on the Fermilab Elastic Analysis Facility (EAF). The EAF is a multi-experiment prototype analysis facility designed to meet the needs of users as datasets grow in complexity and by order-magnitude in size. Commodity components such as Jupyter notebooks, Kubernetes, Dask etc are deployed with the aim of enabling high-throughput, low-latency analysis workflows. Chavez is working on deploying EAF applications and CMS-specific analysis tools for CMS users. As a beta-tester, she provides feedback and suggestions for improvement, while contributing to preparations for upcoming Analysis Grand Challenges, benchmarking and scalability studies.

5.2 GPU Operations

Postdoc Koraka has been working on the commissioning and integration of the recently installed GPU cluster with the CMS production system. In coordination with the CMS PPD and Offline & Computing groups, Koraka facilitated the successful submission of several GPU-enabled workflows through the production system. As a result of this work, GPU-enabled workflows can now be submitted in the regular release validation campaigns and are used to validate software developments and spot differences between CPU and GPU versions of algorithms before they are deployed online. In coordination with different groups working on GPU-enabled reconstruction code developments, Koraka is also working on putting together all the parts of the offline reconstruction that have been ported to run on GPUs, with a goal to have a more complete offline GPU-enabled workflow. The plan is to have offline workflows with increasing percentage of GPU-enabled code first tested using the CMS production system and then run at the High Performance Computing (HPC) centers. HPC machines have good potential to augment CMS computing capabilities in the HL-LHC era and R&D towards efficient GPU-enabled workflows is essential for the next few years.

5.3 Tier-2 facility

The CMS Tier-2 computing center is supported by the USCMS Software and Computing project, an NSF grant at the University of Nebraska. The facility consists of core computing services, which include Unix login, productivity and scientific data analysis software, personal file storage space (on AFS), mail, web, desktop support, backup facility, etc., and the CMS Tier-2 computing center. The personnel for the core computing services are now fully provided by the University.

The US CMS project (NSF) supported researchers Drs. A. Mohapatra and C. Vuosalo, are responsible for the operation of the CMS Tier-2 facility at Wisconsin, which is a 12900-jobslot computing cluster providing 137 KHS06 units of processing power and 11 PB (raw) high-availability distributed storage service. Recently, 24 nodes sporting two NVidia Tesla T4 16 GB GPUs were added using NSF funds. In addition to Tier-2 admin work, Dr. Mohapatra provides operations support for exploiting opportunistic resources for CMS workflows at Open Science Grid (OSG) sites and HPC centers. Dr. Vuosalo provides support for the operation of the Frontier database distribution and squid caching systems. Director of Computing for Physics Department, Mr. D. Bradley, was responsible for innovative software, which takes advantage of widely distributed resources opportunistically using advanced technologies. The UW CMS Tier-2 is based on the HTCondor distributed high-throughput computing technologies developed by the UW Computer Science department, Grid services, and Hadoop-based storage services. The UW Tier-2 facility is unique in its collaboration with a strong computer science team and seamless integration with the campus-wide grid - the UW Center for High Throughput Computing (CHTC) facilities providing about million hours of computing per day - and the nation-wide OSG. We are also providing core middleware for CMS and other grid users nation-wide. Idle Tier-2 resources are available to the full UW HEP group. The UW Tier-2 has always had above-average performance and in fact, is currently the top site in terms of site reliability. It has also been amongst the top contributors for Monte Carlo production among CMS Tier-2 sites. The GPU cluster has been instrumental in helping to commission the CMS HLT for Run 3.

Our Tier-2 facility serves as the primary analysis computing resource for our group and its many collaborators within CMS, besides serving the central Monte Carlo production, data reconstruction and grid-based analysis computing for all CMS users. Local users are involved heavily in the Higgs/EWK measurements and new physics, e.g., $H \to \tau\tau$, b-physics, dark matter and aTGC searches. In addition to the UWCMS team, over 50 CMS-wide users routinely use our systems either through direct login, which takes advantage of opportunistic resources (AAA), or via the OSG or the World-wide LHC Computing Grid (WLCG). Recent achievements made possible by these resources include the analysis of Run 2 data which resulted in several 13-TeV Higgs and diboson production papers and dark matter searches. On demand high priority access to resources while keeping the CPUs active with MC generation in “backfill” mode is crucial for timely completion of analyses. Close collaboration of UW CMS physicists with the NSF-supported computing team results in above average productivity.

6 Activities of UW CMS Faculty

6.1 Professor Sridhara Dasu

Prof. Dasu is involved in physics analysis, trigger operations and upgrade, and computing operations and research. He supervises Scientist Savin, Asst. Scientist Sharma, and the graduate students Mallampalli, Tsoi and Lomte, who are part of this proposal, and the project supported engineers and research software developers. Within CMS, Prof. Dasu represents the UW group at the CMS collaboration meeting and co-chairs the CMS Career Committee. He is currently participating strongly in the LHC Physics Center as a Senior Distinguished Fellow. Beyond CMS, Prof. Dasu played a strong role in the Snowmass 2021 process as a co-leader of the electron-positron collider cross-frontier forum [73]. He currently represents the United States in the International Committee for Future Accelerators (ICFA).

Prof. Dasu worked on SM measurements, Higgs discovery and subsequent studies, and dark matter searches. Prof. Dasu and team focused on exploiting the τ-lepton trigger and reconstruction that they pioneered in CMS. Several graduate students had obtained their PhD degrees developing τ physics tools and analyses. Former group members Bachtis (Ph.D. 2012, now tenured professor at UCLA), Ojalvo (Postdoc 2014-2016, now Asst. Prof. at Princeton), Cepeda (Postdoc 2011-2015, now faculty at CIEMAT, Spain) and Caillol (Postdoc 2016-2021, now Staff at CERN) are successful examples. Prof. Dasu initiated the Wisconsin dark matter search effort, with Gomber (Postdoc 2015-17, now Asst. Prof. U. of Hyderabad, India) and graduate students, using mono-photon, mono-Z, mono-H and mono-Z' events, accompanied by large missing transverse energy. Early papers published using 2016 data show no evidence for anomalous production of mono-objects, but there is left substantial parameter space to be explored. The Higgs discovery and prospects for significantly improved analyses are in a large measure due to the successful measurements of the SM processes done with Scientist Savin. Prof. Dasu ensures that all graduate students and postdocs are also engaged in good quality SM measurements. Following the Run-1 work on $W\gamma/Z\gamma$ (Gray Ph.D. 2012, now FNAL Staff) and ZZ (Ross Ph.D. 2013), WZ Taylor (PhD 2017), Run-2 work thus far has been on the ZZ kinematic distributions (Hussain Ph.D. 2021). Prof. Dasu intends to continue his involvement in the SM multi-boson measurements, Higgs measurements and extended Higgs sector searches, and mono-object dark matter searches, with Savin, Sharma and his students.

Prof. Dasu is responsible for the UW trigger group comprising, Tom Gorski (lead engineer), Ales Svetek (firmware engineer), Jes Tikalsky (software engineer), Kiran Das (firmware engineer) and Robert Fobes (senior technician), in maintaining and operating the layer-1 of the calorimeter trigger in Geneva, and the delivery of hardware, firmware and software for the upgraded calorimeter trigger system, as well as hardware for the correlator and global track trigger systems for the HL-LHC. Prof. Dasu is also responsible for maintenance, operation and upgrades of the UW CMS Tier-2 Computing System with the computing researchers, Dr. Ajit Mohapatra and Dr. Carl Vuosalo. These personnel are funded by the US CMS M&O and S&C or upgrade projects.

Prof. Dasu's current interest is in ensuring the US involvement at the energy frontier [65, 74] beyond the HL-LHC. He is exploring potential of the compact future collider options, both the Cool Copper Collider electron-positron higgs factory [40] and the 10-TeV/10-fb^{-1} muon collider energy-frontier machine [41]. He would like to keep the momentum and follow up on the Snowmass 2021 contributions with solid contributions to the projects blessed in the Particle Physics Project Prioritization Panel process this year. He intends to promote the US P5 plans in international fora, in his role as the US Representative of the ICFA.

6.2 Professor Matthew Herndon

Prof. Herndon's physics studies concentrate on multi-boson production and understanding the gauge structure of the standard model. He is advising graduate students He He, Susmita Mondal, Justin Marquez and supervises Assistant Scientist Dr. Isabelle De Bruyn. He leads the UW effort on the CMS CSC muon project, which includes his advisees, Senior scientist Dr. Armando Lanaro (now retired), Dr. De Bruyn, and graduate students Jithin Madhusudanan Sreekala (Advisor: Dasu) and Wren Vetens (Advisor: Black). On the CMS experiment Prof. Herndon and his advisees have participated in multi-boson cross section measurements in WZ and ZZ at 7, 8 and 13 TeV, searches for EWK production of WZ and ZZ through vector boson scattering, measurement of vector boson fusion to W and Z bosons and anomalous triple and quartic gauge coupling measurements in all of those final states. Following the resent publications of analysis studying the ZZ cross section and effective field theory based aTGC (EPJC with Dr. Hussain, Dr. Savin and former student Dr. Long (CERN Fellow and now MIT researcher)) and EWK ZZ production (PLB with Mr. He and Dr. Savin)(where they studied deep learning techniques for the discrimination of EWK ZZ signal from QCD ZZ background) Prof. Herndon's group is concentrating on further differential measurements of ZZ production. With Mr. He and Dr. Savin they are studying ZZ production with jets (publication expected in early 2022) while with Ms. Mondal and Dr. De Bruyn they are studying Z boson polarization in ZZ production and with Marquez new physics using a full set of dimension 6 effective field theory SMEFT operators. Prof. Herndon has performed many studies of the HL-LHC potential for studying EWK production led the SMP future physics group. The focus of his group on EWK production and polarization is aimed at the eventual goal of measuring the SM QGC and the extraction of the longitudinal component in massive vector boson scattering, which is sensitive to Higgs scattering of the massive vector bosons. Prof. Herndon also participates and coordinates SMP group activities such as Rivet which better enable detailed comparisons of CMS data to the latest theory calculations and event generators. Under the onsite supervision of his scientist, Dr. De Bruyn, Prof. Herndon's personnel participated in successful CSC phase 2 electronics upgrade, installation, and commissioning. Prof. Herndon is also CSC resource manager coordinating personnel and in-kind resource contributions to the international CSC project. He is also the CSC representative on the muon conference and publications committee. Prof. Herndon manages projects such as the production of physical infrastructure including low voltage distribution boxes, thermal coupling materials and chamber covers fabricated by the UW physical sciences laboratory. These items were all successfully installed during LS2. Prof. Herndon works with his advisees on offline monitoring of the CSC performance using T&P techniques. He has improved the detailed monitoring of the CSC hit, segment and trigger primitive (LCT) efficiencies to be fast and robust allowing complete efficiency measurements to be produced on the time scales of days after sufficient data is collected. This upgraded code was used for extensive studies of the Run 2 data to understand readout, HV, and instantaneous luminosity related sources in inefficiency. The code was then successfully employed during Run 3 to produce efficiencies. Detailed information on efficiencies as a function of local coordinates, by strip and wire readout element, hits by layer, kinematic variables, time and number of primary vertices has allowed a complete characterisation of efficiencies and the understanding of most sources of inefficiency. This tool now produces results on short enough time scales that it can, and has, been used to inform decisions on how to set operational parameters of the CSC system in order to maximize the performance of the system. Prof. Herndon also is a member of the permanent organizing committee of the yearly Multiboson Boson Interactions workshop. He also served as US representative to the European VBSCan effort (now concluded). These activities that connect the experimental and theoretical particle physics communities have given him extensive contacts with the theoretical communities engage in multi-boson physics and inform his physics research directions. He also serves on the CDF collaboration publication committee reviewing publication such as the recent CDF W mass result.

6.3 Professor Tulika Bose

Prof. Bose is engaged in physics analysis, trigger tasks, and software & computing efforts. She is currently supervising Asst. Research Scientist Deborah Pinna, postdoc Charis Koraka and graduate students Ganesh Parida, Victor Shang, Elise Chavez and Trevor Nelson. Her physics analysis portfolio covers precision measurements of SM processes ($H \to \tau\tau$ and triple-top) and a wide variety of BSM searches including searches for dark matter, new heavy gauge bosons, top quark partners and vector-like leptons. During the last grant cycle, her student, Andrew Loeliger, graduated with a PhD thesis on precision measurements and searches using the $H \to \tau\tau$ final state and is currently a postdoc at Princeton. Prof. Bose's team members play important roles in L1/HLT and software & computing operations/development and/or upgrade studies.

The success of the physics program of the CMS experiment critically depends on its ability to store, process, and analyze its big datasets in an efficient and timely manner. In 2019, Prof. Bose was recruited to take on the responsibility of Deputy U.S. CMS Software and Computing Operations program manager. In this position, she helps oversee a program that funds software and computing related activities at 17 different U.S. CMS institutes. These activities enable expeditious processing of CMS data allowing US physicists to take on leadership roles in CMS physics. Prof. Bose herself is coordinating an effort targeting modernization of CMS software and computing infrastructure via the integration of heterogenous computing resources (e.g. GPUs). This includes integrating both local resources as well as utilizing GPU allocations at various DOE/NSF-funded HPC centers via workflows that can offload code to GPUs. This R&D effort is critical for enabling CMS to meet the computing challenge of the HL-LHC era.

Previously, Prof. Bose served as the CMS Physics Co-coordinator (PC) (Sep 2017 – Aug 2019). This was a top-level management position within international CMS and she was one of two lead scientists charged with overseeing the entire scientific output of the CMS experiment. She helped define the goals and types of research that collaborators undertook as they moved towards fully understanding the nature of electroweak symmetry breaking and potentially discovering new physics. She was responsible for organizing activities to produce and review all of the physics results of the CMS experiment. Under Prof. Bose's leadership, CMS submitted a record number of papers for publication with nearly 270 papers being submitted during her stint as PC. Prof. Bose strengthened connections with the theory/phenomenology community with invited talks, improved communication of physics results via the introduction of CMS Physics Briefings and successfully engaged the collaboration in a long-term physics planning effort.

In addition to serving as the CMS PC and supervising her postdocs and students over the years, Prof. Bose has made several other major contributions to the CMS physics effort. She served as the co-convener of the CMS Electroweak Diboson sub-group in 2011. The results from the diboson cross section measurements in 2011-2012 helped validate the reliability of the background estimation techniques used in the Higgs searches culminating with the Higgs discovery in 2012. Prof. Bose served as the co-convener of the CMS Beyond Two Generations (B2G) Resonances sub-group from July 2012 - August 2014 and as the CMS B2G L2 co-convener from 2016 - 2017. Under her leadership, the group published a large number of papers using the 2015 and 2016 datasets.

Prof. Bose has also been engaged in the CMS trigger effort since 2006. She was responsible for the HCAL trigger emulation code at the start of Run 1, played a leading role in the commissioning of the CMS High-Level Trigger and as a convener of the CMS Trigger Studies Group (TSG) oversaw the successful development, optimization and deployment of trigger menus online for the 7 TeV run. She was then appointed as the CMS Deputy Trigger Co-coordinator in 2011 and prior to the start of Run 2, she was appointed as the CMS Trigger Co-coordinator (2014-2016). Bose's successful leadership of the TSG during this critical period led to successful Run 2 data-taking operations and the collection of a rich physics dataset that has yielded many publications for CMS.

Prof. Bose was elected as an APS Fellow in 2019 for "leadership coordinating the CMS physics program and trigger system, and for contributions to the development of high level triggers and searches for heavy vector bosons and vector-like quarks". Her expertise in BSM searches led to her being chosen as the topical group leader of the Snowmass Energy Frontier "EF09: BSM – more general explorations" group. As part of this effort, she worked with other frontiers to help carve the vision for BSM physics. She also served as one of the co-conveners of the DOE Basic Research Needs (BRN) Study on HEP Detector R&D with her charge covering "Trigger and Data-Acquisition (including Machine Learning)". For this effort Prof. Bose worked on determining priority research directions and technological breakthroughs needed for expanding experimental capabilities at next-generation experiments within the Energy, Cosmic and Intensity/neutrino frontiers. Prof. Bose was recently appointed as a member of the Particle Physics Project Prioritization Panel (P5) panel charged with providing a long-term strategic plan for U.S. investments in particle physics.

Prof. Bose was elected as the Secretary/Treasurer of the APS Division of Particles and Fields (DPF) Executive Committee in 2022 and has previously served on the Fermilab Users' Executive Committee and the US LHC Users Association Executive Committee. She was recently elected to the AURA Management Council for the Vera C. Rubin Observatory (AMCR). She has served on the program committee of several conferences and is the Deputy chair of the International Advisory Committee of the LHCP conference series, a major international conference for the LHC/collider community. She also serves as Associate Editor for the journal European Physical Journal C. Prof. Bose has a keen interest in outreach, science communication and improving diversity and inclusion. She co-organized the U.S. CMS PURSUE program [75] for minoritized undergraduate students, is on the Advisory Committee for Symmetry magazine, is currently the chair of the Physics Department Climate & Diversity committee and a member of the University Faculty Senate.

6.4 Professor Kevin Black

Prof Black has led efforts on the development of the readout and trigger electronics for the forward GEM detector. As US L3 for the GEM upgrade project, he manages the US GEM effort consisting of a team of electronics engineers, scientists, and postdocs from UCLA, Rice Univ., TAMU, UC Davis, Florida Tech, and the University of Wisconsin. Prof. Black has leadership roles within international CMS and serves as the CMS GEM Electronics coordinator and was recently CMS Deputy GEM Run and Commissioning coordinator responsible for the installation and commissioning of the GEM detectors. His students and post-docs are currently working on the xDAQ software (Galloni, Teague), electronics noise protection (Galloni, Vetens, Teague), and GEM calibration and associated software (Galloni, Teague).

Prof. Black supervises post-docs and students in the development of software and analyses ranging from the identification of low momentum taus (Galloni), tests of lepton universality in the b-sector (Galloni), searches for rare top quark production (Pinna, Teague), and searches for di-higgs resonances (Galloni, Aravind), searches for long lived particles (Warden), and searches for exotic dark matter(Vettens). In addition, Black has been the LPC co-coordinator since 2020, member of the CMS diversity committee, and also currently chairs the implementation taskforce for diversity and inclusion in CMS (ITDI). Prof. Black played an active part in the Snowmass process in 2021-2022. He was co-chair of the muon collider forum and co-author of the muon collider forum report summarizing the studies and case for future development of R&D for a muon collider. As well he was co-editor of the micropatern gas detector MPGD for future colliders group. In all he contributed to six snowmass papers with students, post-docs, and as an editor. For 13 years (5 as a post-doc at Harvard and 8 as a faculty member at Boston University), Prof. Black worked on the ATLAS experiment. He had several leadership roles in the ATLAS and US ATLAS organization, in the upgrade project, in trigger development and operations, and in physics analysis. His analysis efforts covered a broad range of topics including top quark physics, exotic searches, standard model measurements, and Higgs boson searches. Prof. Black held a L1 position within US ATLAS and served as the Deputy L1 physics support manager for US ATLAS managing a team of scientists and computing professionals who reported to him and helped support the ATLAS physics program.

Prof. Black was the subgroup convener of the ATLAS HQT (heavy quarks and top) exotics group and oversaw searches for new physics with heavy quarks (2014-2015). Prof. Black, with his students and post-docs, had leadership roles in the first ATLAS paper on the evidence of the Higgs boson coupling to tau leptons (Dell Asta), conducted searches for heavy vector like top quarks (Bernard), measured the W and Z cross-sections with first Run 2 data (Dell Asta, Sherman), and most recently, led the effort towards the first observation of single top quark production in association with a Z boson (Dell Asta, Sherman)

Prof. Black was the US L3 manager for the L0MDT project on ATLAS in a collaboration of 3 US institutions (BU, UMASS, and UC Irvine) and two international partners (Tokyo and MPI). This project will replace the backend electronics for the ATLAS drift tubes as well as add the drift tubes into the L0 muon trigger with an ATCA based architecture blade. In addition he co-lead the ATLAS muon trigger and performance group between 2013-2015 and his group helped rewrite the L2 muon trigger suite.

Name	Unit	Level	Position
Kevin Black	USATLAS	Level-3	Manager, L0MDT Upgrade (2016-18)
	USATLAS	Level-2	Manager, Physics Support (2016-18)
	ATLAS	Level-3	Convener, Heavy Quark Exotics Subgroup (2013-14)
	ATLAS	Level-3	Coordinator, Muon Trigger (2012-16)
	ATLAS	Level-3	Convener, Lepton+X Exotics Subgroup (2006-10)
	ATLAS	Level-3	Coordinator, Muon Commissioning Software (2008-10)
Tulika Bose	CMS	Level-1	Physics Co-coordinator (2017-19)
	CMS	Level-2	Co-convener, B2G Physics Analysis Group (2016-17)
	CMS	Level-1	Trigger Co-coordinator (2014-16)
	CMS	Level-3	Co-convener, B2G Resonances Subgroup (2012-14)
	CMS	Level-1	Trigger Deputy Cordinator (2011-13)
	CMS	Level-3	Co-convener, EWK Diboson Subroup (2011)
	CMS	Level-2	Co-convener, Trigger Menu Group (2007-11)
Sridhara Dasu	USCMS	-	Chair, USCMS Collaboration Board
	CMS	Level-3	TriDAS Resource Manager (2012-14)
	CMS	Level-3	Co-convener, Higgs to Taus Subgroup (2012-13)
	CMS	Level-2	Upgrade Physics Coordinator (2010-11)
	CMS	Level-2	Co-convener, EWK Physics Analysis Group (2008-09)
	CMS	Level-2	Co-convener, Online Selection Group (2005-07)
Matt Herndon	CMS	Level-3	Co-convener, SMP Future Physics (2015-17)
	CMS	Level-3	Co-convener, SMP Multiboson Subgroup (2012-13)
Sascha Savin	CMS	Level-2	Co-convener, Upgrade Physics Studies (2019-22)
	CMS	Level-2	Co-convener, SMP Physics Analysis Group (2013-15)
	CMS	Level-2	Co-convener, Tau Physics Objects Group (2012-13)
	CMS	Level-2	Co-convener, Trigger Performance Group (2008-11)
Isa De Bruyn	CMS	Level-3	Manager, CSC Upgrade (2019-21)
	CMS	Level-3	Deputy Manager, CSC Upgrade (2018)
Deborah Pinna	CMS	Level-3	Co-convener, MET+X Subroup (2020-22)
Varun Sharma	CMS	Level-2	L1 Trigger Tech Coordinator (2020-22)

Table 2: Past management positions held by the UW CMS group members are shown, including the level of positions in the ATLAS, CMS or US CMS organization charts, where applicable.

Dr. Savin's Graduate Advisees					
Name	Ph.D. Year	Name	Ph.D. Year	Name	Ph.D. Year
He He	2023 (exp)	Usama Hussain	2020	Kenneth Long	2019
Nate Woods	2017	Devin Taylor	2017	Tom Perry	2016
Ian Ross	2013	Joshua Swanson	2013	Michail Bachtis	2012
Marc Weinberg	2011	Homer Wolfe	2008	Erik Brownson	2008
Tom Danielson	2007	Adam Everett	2006	Pat Ryan	2006
Michele Rosin	2006	Liang Li	2005		
Dr. Savin's Postdoctoral Advisees					
Name	Years	Name	Years	Name	Years
Varun Sharma	2017-present	Cecile Caillol	2016-2021	Senka Duric	2013-2018
Maria Cepeda	2011-2017	Evan Friis	2011-2013	Dorian Kcira	2000-2005

Table 3: Dr. Savin assists the faculty, Dasu, Herndon and in the past Smith, in supervising students and postdocs stationed at CERN. The table lists the groups of students and postdocs who worked under his advice.