1 Overview

The University of Wisconsin faculty Kevin Black, Tulika Bose, Sridhara Dasu and Matthew Herndon propose to continue their leading roles in the Compact Muon Solenoid (CMS) experiment [1] at the LHC, as we explore proton-proton collisions at 13.6 TeV and prepare for future higher luminosity running. Presently the UW group includes senior scientists Alexander Savin and Pieter Everaerts, junior scientists Camilla Galloni, Abdollah Mohammadi, Deborah Pinna and Varun Sharma, postdoc Charis Koraka, and twenty graduate students, supported by eight engineers and computing experts.

The UW group is leading physics analyses in the 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 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 the then scientists Richard Loveless and Sridhara Dasu in 1993. Prof. Matthew Herndon joined the group in 2010 and Prof. Kevin Black and Prof. Tulika Bose in 2018. The group is playing strong roles in electroweak, higgs and new physics analyses, graduating 31 PhD students and mentoring 13 postdocs/scientists. Of particular note are the five postdocs/scientists who moved on with success, securing faculty or staff scientist positions at prestigious places around the world and two graduate students who won the best CMS theses of the year awards.

1.2 Proposed Research Directions

The primary mission of the LHC is to search for new physics phenomena: discovering the nature of dark matter, hunting for new particles and understanding the mass generation mechanism. This involves deep study 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 di-Higgs resonances, vector-like leptons, low mass exotic quark bound states and multiple top quarks production.

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 (2022-26, 13.6 TeV, 196 fb^{-1} in 2022-24 with >300

Name	Unit	Level	Position
Prof. Kevin Black	CMS	Level-2	GEM IB Chair
	USCMS	Level-3	GEM Electronics Project Manager
	USCMS	-	LPC Management Board
	IMCC	-	Member, Paper and Speakers Board
	USMCC	-	Member, Paper and Speakers Board
Prof. Tulika Bose	CMS	-	Member, Collaboration & Management Boards
	CMS	-	Heterogeneous Architectures Officer
	USCMS	Level-1	Manager, Software & Computing
Prof. Sridhara Dasu	CMS	Level-1	Deputy Chair, Collaboration Board
	CMS	-	Member, Collaboration & Management Boards
	USCMS	Level-3	Manager, HL-LHC Calo Trigger Upgrade
	IMCC	-	Member, Steering Committee
	USMCC	-	Member, Interim US Muon Collider Leadership
Prof. Matthew Herndon	CMS	Level-3	CSC Resource Manager
	USCMS	Level-2	EMU Deputy Operations Manager
Dr. Pieter Everaerts	CMS	Level-2	GEM System Manager
Dr. Alexander Savin	CMS	Level-3	Co-convener, HL-LHC Calo Trigger Upgrade
Dr. Camilla Galloni	CMS	Level-3	GEM Run Coordinator
Dr. Charis Koraka	CMS	Level-3	Very Heavy Fermions sub-group of B2G PAG
	CMS	Level-3	GPU reconstruction, CMS Offline & Computing
Dr. A. Mohammadi	CMS	Level-3	Co-convener, Third gen sub-group of NPS PAG
Dr. Deborah Pinna	LHC	-	Co-organizer, LHC Dark Matter Working Group
Dr. Varun Sharma	CMS	Level-2	Trigger Technical Coordinator

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

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 group exploited the full Run-2 dataset in the final stages of publications. The group proposes to complete several Run-3 and combined Run-2,3 analyses during the coming years, in addition to preparing the experiment for future high luminosity operations.

The complexity of physics signatures, backgrounds, detector conditions of full Run-2 and Run-3 data already mandates us to use multi-variate techniques based on Machine Learning (ML) tools. The UW group has deployed ML techniques in many of 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 and offline usage and for the successful execution of ML techniques, which are very resource intensive.

Run-3 began operating at 13.6 TeV center-of-mass energy in 2022. The UW group work during the long shutdown 2 (LS2) in preparation for the Run-3 involved, EMU CSC chamber upgrades, addition of new EMU GEM chambers, level-1 trigger firmware improvements, and HLT development and commissioning. The (re)commissioning and diligent preparation for data quality monitoring have paid off well. Good quality data collection has resulted in an accumulation of about 196 fb^{-1} in the 2022-24 runs and nearly 50 fb^{-1} in 2025. Analyses are being conducted using improved smaller sized data formats such as the nano-AOD. The group has actively engaged in several Run-3

and combined Run-2,3 analyses based on this data. Run-3 routinely involves continuous running at instantaneous luminosities, upwards of $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, 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 were developed for Run-3 operations based on the implementation of machine learning - anomaly detection in our FPGA trigger platform using High-Level Synthesis (HLS). We have also upgraded the HLT code to use GPUs, playing a critical role in its commissioning.

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 remaining 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. 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. The group is also deeply engaged in planning for LS3 upgrade, installation, and commissioning activities and will participate in these activities across all of the group projects.

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.

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 studies of the electroweak gauge sector, the 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 including vector boson scattering, 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 Dr. Savin focus on supervision of the SM measurements and associated new physics phenomena. Prof. Dasu works

with Dr. Sharma, focusing on SM Higgs characterization, new physics in the Higgs sector and dark matter searches. Prof. Bose works with Dr. Pinna and Postdoc Koraka on searches for heavy new particles involving resonances of higgs pairs, vector-like leptons, dark matter, and triple top quark production. Prof. Black works with Dr. Everaerts and Dr. 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.

Dr. Savin and Dr. Sharma (Level-1 trigger), Dr. Pinna (High Level Trigger, EMU), Dr. Everaerts and Dr. Galloni (EMU), and Dr. Koraka (Software & Computing) 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 train our graduate students in making measurements in the context of the Standard Model and also search for new physics in similar final states, as well as gain well-rounded experience 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. Past positions held by the group members are in Table 2.

2.2 Electroweak Physics

Measuring SM electroweak (EW) 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). Presently, Prof. Herndon is a co-convener of the LHC-wide Electroweak physics working group (EW WG) which brings together the four experiments and theorists to jointly work on EW physics issues. 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.

The UW group has a strong effort in analysis and leadership in the multi-boson subgroup (past conveners Bose, Herndon, Duric, Long). Current UW analysis projects focus on QCD induced di-boson production and EW production of multiple heavy gauge bosons. The measurements encompass production cross sections, differential cross sections, vector boson polarization, anomalous triple gauge couplings of vector bosons (aTGCs), anomalous quartic gauge couplings (aQGCs), effective field theory searches, and the study of the pure EW 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.

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 Dr. Savin performed a search for EW WZ production and quartic gauge coupling and in WZ vector boson scattering and an associated search for charged Higgs production via vector boson fusion [31]. Following this, graduate student Hussain (Advisor: Dasu, Ph.D 2019) with Long, Prof. Herndon and Dr. Savin 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.

2.2.1 Recent results: ZZ production with jets and Electroweak Production

He, Savin, Herndon

Graduate student He (Advisor Herndon) with Dr. Savin worked on developing 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 in the ZZ with two jets final state [32]. Mr. He, Dr. Savin and Prof. Herndon expanded this program of research to include differential measurements vs. the number of jet produced in ZZ production and also subdividing the 4 lepton invariant mass space in different regions 1 [33]. In addition, graduate student Mondal (Advisor Herndon) produced NNLO cross section prediction comparisons included in this paper.

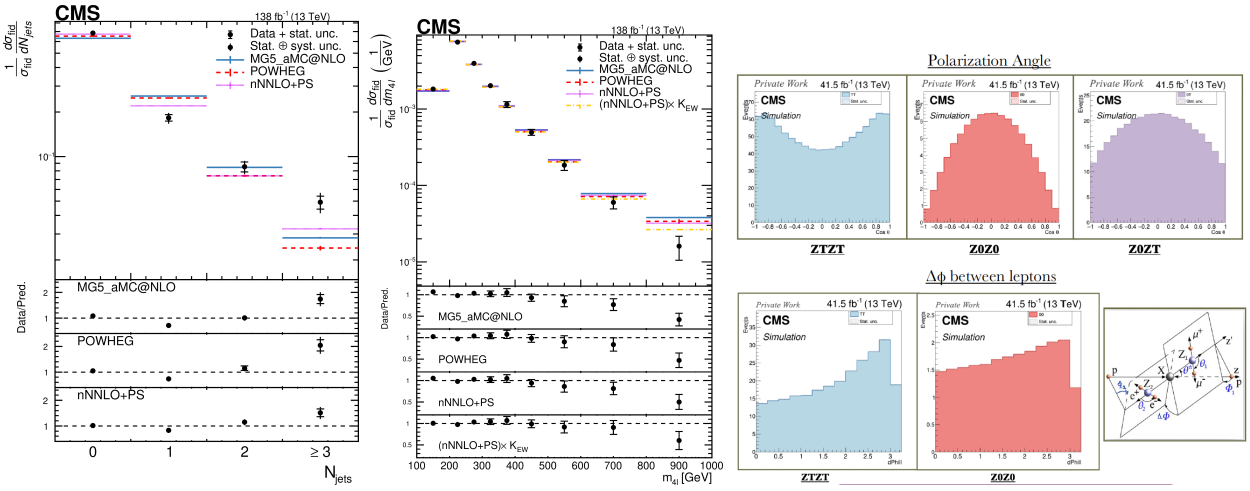

Figure 1: From the ZZ+jets analysis. Distribution of jets in 4l events(left). DiJet mass distribution in 4l event(center). (He, Herndon & Savin) From the ZZ polarization analysis. Angular distributions sensitive to polarization using 13 TeV MC simulation including the lepton angle relative to the flight direction of the Z boson in the Z rest frame and the difference in ϕ between the two leptons of the same sign from the two Z decays in ZZ production(right). (Mondal, Herndon & Savin)

2.2.2 Current research: ZZ Polarization including Run 3 data

Mondal, Savin, Herndon

Mondal, with Prof. Herndon and Dr. Savin, is currently performing an analysis of vector boson polarization in inclusive ZZ production that will use the combined Run 2 and Run 3 datasets. The existence of the longitudinal polarization state for massive vector bosons is a consequence of the Higgs mechanism. In addition, the fractions of longitudinal and transverse polarization are energy dependent and the analysis will include measurements as function of the ZZ system center of mass energy which allows the combination of the Run 2 and Run 3 data. The angular distributions sensitive to polarization using 13 TeV MC simulation are shown in figure 1 including the lepton angle relative to the flight direction in the Z rest frame and the difference in phi between the two leptons of the same sign from the two Z decays in ZZ production. The full dataset is expected to be sufficient to achieve observation of longitudinally polarized Z bosons in ZZ production. New MCs that allow tracking of polarization information and NLO generation are essential to these studies.

2.2.3 Current research: Run 3 13.6 TeV ZZ cross section measurements and EFT

Marquez, Savin, Herndon
Graduate Student Marquez (Advisor Herndon) and Dr. Savin are engaged in the first Run 3 13.6 TeV measurement of the inclusive ZZ production cross section. Marquez, with Prof. Herndon and Dr. Savin, will also perform an effective field theory search using a complete set of dimension 6 standard model effective field theory (SMEFT) operators that are expected to have effects on the rate and distributions, including angular polarization distributions, in ZZ production. The use of the angular distributions sensitive to polarization is particular useful for EFT measurements in that it allows the discrimination between different types of new physics that couple to the longitudinal or transverse polarization of the vector bosons.

2.2.4 Proposed research: EWK multi-boson production & polarization.

Austin, Savin, Herndon
Integral to searching for di-boson production though purely EW scattering is studying the polarization of the scattered vector bosons to disentangle the contributions of longitudinal vector boson scattering via the Higgs from scattering of the 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 EW di-boson production searches through graduate students Long and He's analysis with Prof. Herndon on EW 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]. Mondal is performing her thesis research on measuring the polarization of Z bosons in inclusive ZZ production and an analysis of the dependence of polarization on the energy of ZZ pairs. Graduate student Marquez is studying using polarization and other angular or energy dependent variables to enhance the sensitivity of ZZ data to anomalous couplings. The UW group proposes to conduct and to extend these studies using to the full Run 2 and Run 3 datasets to observe EW scattering in the ZZ state and study the polarization of the scattered vector bosons. The combined dataset should be sufficient to both observe EWK ZZ scattering and establish or set limits on the participation of at least one longitudinal vector boson in that process. ML discrimination techniques will be essential to accomplishing these measurements with the LHC data through Run 3. New and future students such as graduate student Austin will participate in these analyses.

2.2.5 Proposed research: Radiation Amplitude Zero Effects in WZ events

Martinez, Black, Herndon
Graduate student Martinez (Advisor: Black, Herndon) and Dr. Savin propose to make a measurement of the Radiation Amplitude Zero (RAZ) Effect in WZ diboson events. A key prediction of the Standard Model is that the breaking of electroweak symmetry provides not only mass but also a longitudinal polarization of the W and Z gauge bosons. While this can in principle be tested by studying VBS, due to the low cross-sections this has only been seen so far at the 3σ level. On the other hand in inclusive vector boson production all polarization configurations can be sutdied in more detail. It has been shown that because of the left-handed coupling of the W boson, there exists an angle between the W and Z boson in the center-of-mass frame where the helicity amplitude uniquely vanishes for transverse polarized vector bosons with opposite transverse polarization. This

is given by $cos(\theta) = \frac{\alpha}{\beta}(\frac{g^{f_1}+g^{f_2}}{g^{f_1}-g^{f_2}})$ where the g's are the coupling of the two fermions to the Z boson and $\alpha = 1 - r_W - r_Z$ and $\beta = (\alpha^2 - 4r_W r_Z)^{\frac{1}{2}}$ and $r_V = \frac{M_V^2}{s}$ and s is the standard Mandelstam variable and the square root of the center-of-mass energy in the parton frame as first shown in [35]. In addition, in TT production this can be understood as an exact cancellation between the triple gauge coupling diagrams (TGCs) and diagrams where the W and Z are radiated from quark lines at the RAZ point making the observation of RAZ a method to observe a significant effect induced by the presence of TGSs in WZ physics. These effects are predicted by simple leading order calculation. Next-to-leading order (NLO) predictions prediction change the polarization and helicity amplitudes and introduce a larger component of final states with no definite state such that the RAZ effect is significantly reduced. However, by using selections to remove events with NLO like topologies involving one jet the RAZ can largely be restored [36]. By measuring the cross-section as a function of variables sensitive to this angle, the ATLAS collaboration has shown that the dip due to this effect from transverse polarized WZ exists. While ATLAS has now measured this effect to 5σ [37], CMS does not have such an analysis. We propose to use all of the Run 3 data which should allow us to observe the effect and begin making precision tests of the SM and alternative couplings which would lead to variation from the SM.

2.2.6 Current Research: $W \to 3\pi$ search

Nee, Sharma, Dasu

The rare $W \to 3\pi$ decay channel was first explored by our former postdoc Calliol, resulting in an early publication [38]. Prediction of the branching fraction is fraught with hadronic uncertainties, so an experimental measurement is necessary. A measurement, if the rate is sufficiently high, could help with the understanding of this hadronization process. The relatively low mass of the W makes the purely hadronic decay channel difficult to trigger at the LHC, although the excellent offline tracking resolution makes the process very much accessible. However, graduate student Nee was instrumental in identifying that the machine learning based trigger CICADA, which our group developed with Princeton, is more efficient than the standard CMS triggers, for the $W \to 3\pi$ final state (See Figure 14). Nee is continuing this effort to potentially measure $W \to 3\pi$ branching fraction.

2.3 Higgs Physics

2.3.1 Prior Results: SM Higgs Decays to Z pairs in lepton modes

Profs. Dasu, Smith and Dr. 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. Our 4-lepton group effort has morphed to detailed studies of Z-pair processes.

2.3.2 Prior Results: 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 Dr.

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 (See Figure 2). Loeliger (Ph.D. 2022, 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 [39], extraction of the fermion and vector boson Higgs couplings [39] and measurement of differential kinematic distributions [40].

2.3.3 Recent Results: Boosted SM Higgs Decays to tau pairs

Mettner, Mohammadi

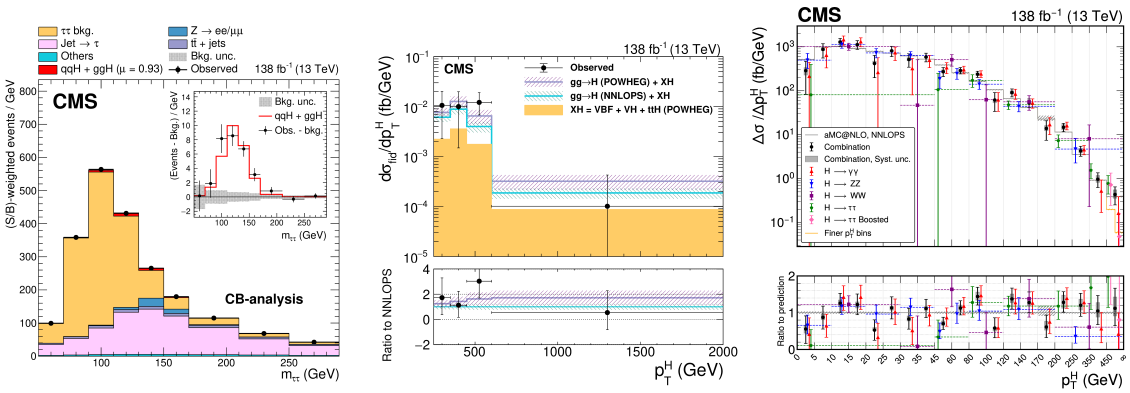

Figure 2: Full Run-2 $H \to \tau\tau$ analysis published in 2021 (left). Observed and expected differential fiducial cross sections as functions of p_T^H (middle) in boosted $\tau\tau$ analysis in 2024.

Dr. Mohammadi played a leading role in the first LHC measurement of boosted Higgs bosons in $\tau\tau$ final state (See Figure 2) [41]. The analysis required special developments both at trigger and reconstruction levels to avoid self-veto of the τ-pair events, as the normal τ-reconstruction relied heavily on the charged-track counts and isolation. Further detailed characterization of boosted-higgs reconstruction was done by student Mettner. Boosted-τ reconstruction techniques were necessary to obtain these results. The Run-3 version of this analysis will be undertaken by graduate student Nelson (Advisor: Bose) and Dr. Mohammadi, leveraging work done in the context of our di-Higgs searches 2.4.2.

2.3.4 Proposed Research: SM Higgs Decays to tau pairs

Alharthy, Mettner, Mohammadi, Savin, Dasu

Dr. Mohammadi, graduate students Alharthy (Advisor: Dasu) and Mettner (Advisor: Dasu) are reviving the collaboration to re-measure accurately $H \to \tau\tau$ using all Run-3 data. The porting

of the code base to newer analysis frameworks, Coffea, is beginning. The goal is to make a comprehensive measurements using both resolved, boosted and VBF modes, focusing on purity, and extract differential distributions. There is significant opportunity to update the machine learning and boosted τ techniques deployed in earlier measurements, realizing improved measurements.

2.3.5 Proposed Research: SM Higgs Decays to $b\bar{b}$

Lomte, Simeon, Caron, Korupulu, Savin, Sharma, Dasu

Dr. Savin, Dr. Sharma, graduate students Lomte (Advisor: Dasu) and Simeon (Advisor: Dasu), and undergraduate students Caron and Korupulu have begun a collaboration to measure the Higgs boson decays to $b\bar{b}$. Their goal is to include all of Run-3 data and as many modes as possible, focusing on purity of signals. Work involves using machine learning techniques in the analysis to lower the backgrounds and unfolding Higgs kinematic distributions. They plan to reduce systematic uncertainties and extract differential cross sections in preparation for the HL-LHC exploitation. The students have started using modern analysis frameworks, owning one or more decay modes of the Z-boson for targeting the ZH production channels.

2.3.6 Recent Results, Proposed Research: SM Higgs Combination

Mohammadi, Dasu

The group efforts on Run-2 SM Higgs analyses in τ-pair modes, including Dr. Mohammadi's newest boosted analysis, were part of the CMS higgs-analyses wide combination paper (See Figure 2) [42]. The boosted τ-pair analysis makes significant contribution in the important high-p_T region.

2.3.7 Proposed Research: SM Higgs Precision Physics

Mohammadi, Savin, Sharma, Dasu

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 three years they propose to develop improved analyses to obtain the best differential cross section measurements in both $b\bar{b}$ and $\tau^+\tau^-$ modes. This program will continue through HL-LHC resulting in publications whenever accumulating data doubles. We anticipate continued participation in combination analyses of Run-3. However, these combinations lag behind individual measurements and are anticipated to be feasible only at the end of this research proposal timeline.

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 Higgs Factory (Cool Copper Collider [43]) and Muon Collider [44] programs, and expects to continue to do so.

2.3.8 Proposed Research: Lepton Flavor Violating H(125 GeV) Decays

Sharma, Dasu

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]. Dr. Sharma, in collaboration with Notre Dame and CERN groups, completed a comprehensive Run-2 analysis [18, 45, 46]. Since these analyses are only statistically limited it behooves us to continue this search for lepton flavor violation. Dr. Sharma and future graduate students will revive this analysis, together with prior collaborators, after the completion of Run-3.

2.3.9 Current Research: Light Pseudo-scalar Higgs Searches in H(125 GeV) Decays

Aravind, Everaerts, Black

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, graduate student Tsoi (Ph.D. 2024, Best CMS Thesis Award, Advisor: Dasu) and Dr. Everaerts have completed a full Run-2 search for this a-boson in the modes $h \to aa \to \tau^+\tau^- b\bar{b}$ using partial Run-2 data [10].

Graduate student Aravind (Advisor: Black) and Dr. Everaerts are extending this for exotic decays of the Higgs boson into light psuedoscalars a_1 and a_2 where one psuedoscalar decays into a pair of τ leptons and the other decays into a pair of b-quarks where the masses of the two psuedoscalars can be significantly different. Backgrounds are estimated from a combination of monte carlo simulation, embedded τ samples, and multijet data events. A Boosted Decision Tree is used to optimize the separation between signal and background and then the di-τ invariant mass is used to search for signal events or set limits. Figure 3 shows the invariant mass in the $Z \to \tau\tau$ control region, signal region, and the expected limits in the two pseudoscalar mass ranges. The analysis is expected to be published in early 2026.

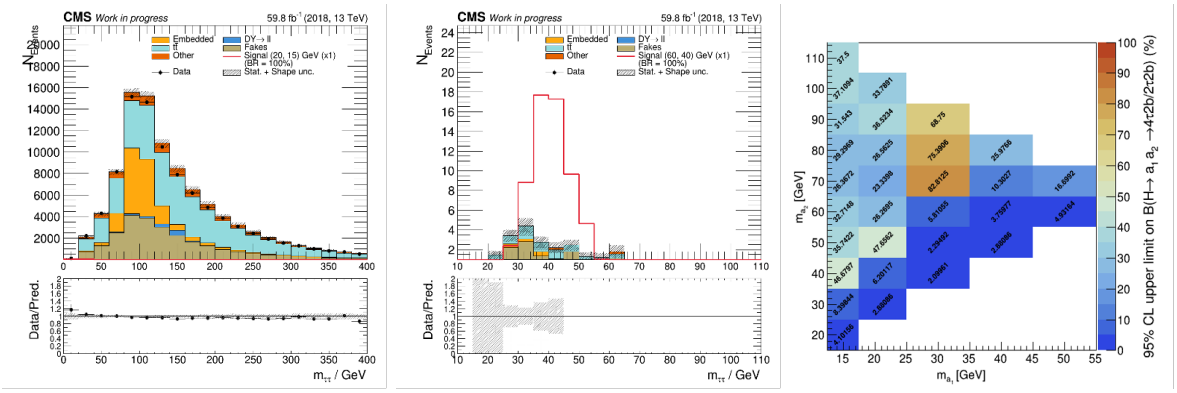

Figure 3: Invariant mass of τ pairs in the Z control region (left), blinded signal region, and the expected limits of the search (right) (Aravind, Everaerts, Black)

2.4 Searches for Di-Higgs Resonances and BSM Higgs Bosons

While SM di-Higgs production offers a direct probe of the Higgs self-coupling and is essential for mapping the shape of the Higgs potential, its predicted cross-section is extremely small. As a result, meaningful observation is unlikely until the full High-Luminosity LHC (HL-LHC) dataset becomes

available. In contrast, several well-motivated BSM scenarios predict enhanced di-Higgs production via heavy resonances decaying into Higgs boson pairs. These include, for example, Kaluza-Klein (KK) excitations of spin-0 radions and spin-2 gravitons, which arise in extra-dimensional models. Our group is actively engaged in multiple searches targeting such high mass resonant di-Higgs signatures. Given the TeV-scale masses of interest, the resulting Higgs bosons are often highly boosted, necessitating specialized reconstruction and substructure techniques. To address this, we have taken a leading role in developing machine learning-based algorithms for the identification and reconstruction of boosted tau leptons—key decay products in several di-Higgs final states. These tools are integrated into our analyses and have proven critical in enhancing sensitivity to new physics. Our broader expertise in searches with boosted objects [47, 48, 49] continues to inform and strengthen our searches in this area.

While the SM Higgs sector is minimal with only one doublet scalar field, supersymmetric and other BSM theories have extended Higgs sectors with several heavy and sometimes lighter scalar and pseudo-scalar bosons. We have searched for many such particles in the past [12, 13, 14], and wish to revive those searches with the full luminosity of Run-2 and Run-3.

2.4.1 Recent Results: Heavy resonances decaying into the $HH \to b\bar{b}\tau^+\tau^-$ final state

Parida, Galloni, Pinna, Bose

Graduate student Parida (Advisor: Prof. Bose) has led a comprehensive search for narrow, high-mass resonances in the $HH \to b\bar{b}\tau^+\tau^-$ final state, in collaboration with Dr. Galloni and Dr. Pinna. This full Run 2 analysis incorporates several innovative techniques developed by our group to significantly enhance sensitivity. A key advancement was the development of a dedicated deep learning-based tagger—referred to as the Boosted DeepTau tagger—specifically optimized for the identification of boosted tau leptons. This tagger leverages both high-level features from tau reconstruction and low-level detector inputs to effectively distinguish genuine boosted taus from background jets. Compared to the previously used boosted decision tree-based discriminator, the Boosted DeepTau tagger demonstrates a 2–4$\times$ improvement in discrimination power for taus with $p_T < 100$ GeV, and over a 10$\times$ improvement for $p_T > 100$ GeV. Although designed for this analysis, we have made the tagger available for broader use within the CMS collaboration [47]. A second major innovation was the integration of a graph convolutional neural network-based tagger, ParticleNet, for identifying merged $b\bar{b}$ jets. This approach significantly improves jet substructure classification, especially in the high-mass regime where jet merging is prevalent. Together with refined signal optimization and background estimation strategies, these advancements enabled our team to set the most stringent upper bounds to date on the production of resonant $X \to HH \to b\bar{b}\tau^+\tau^-$ at the LHC, for resonance masses from 1.4 to 4.5 TeV. The analysis was released for public dissemination just recently in time for the Lepton Photon Conference [50] and the paper is expected later this year.

2.4.2 Current Research: Heavy resonances decaying into the $HH \to \tau^+\tau^-\tau^+\tau^-$ final state

Nelson, Galloni, Pinna, Mohammadi, Bose

Graduate student Nelson (Advisor: Prof. Bose) is leading a pioneering search for new heavy resonances in the $HH \to \tau^+\tau^-\tau^+\tau^-$ final state, in collaboration with Dr. Mohammadi, Dr. Galloni, and Dr. Pinna. This analysis represents the first exploration of the > 1 TeV mass regime in this channel at the LHC, extending beyond the scope of previous searches which were limited to resonance masses below 1 TeV. The choice of the four tau final state is motivated by the relatively high branching ratio of $H \to \tau^+\tau^-$ and the potential for improved signal-to-background discrimination

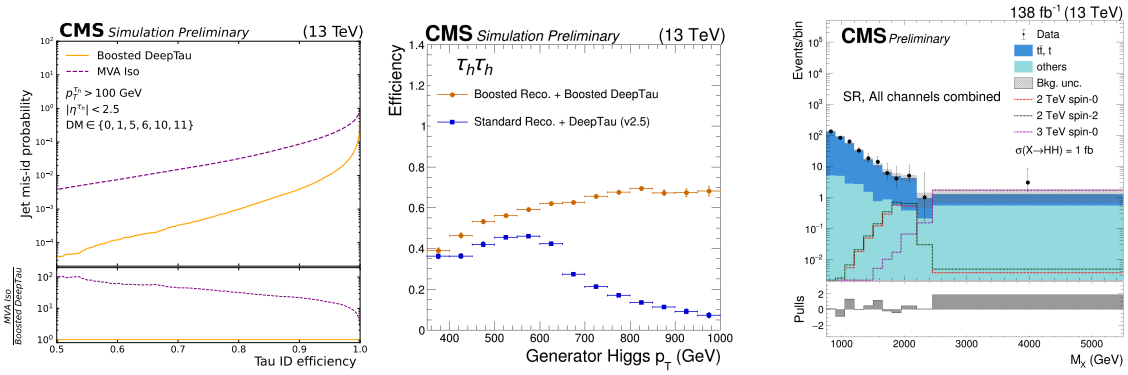

Figure 4: ROC curves for the Boosted DeepTau algorithm developed by our group showing a $10x$ improvement over the previous tagger (left), improvement in the efficiency coming from the boosted tau reconstruction and newly developed Boosted DeepTau tagger (middle), and resonance mass distribution after applying all selection criteria(right). [Parida, Galloni, Pinna, Bose]

compared to final states such as $H \to b\bar{b}$. This analysis thus provides a complementary avenue for probing high-mass di-Higgs production, particularly in scenarios predicted by BSM models involving heavy resonances.

Currently under development using the full Run 2 dataset, the analysis will incorporate advanced techniques developed by our group, including the Boosted DeepTau tagger for identifying highly boosted taus. Early efforts have also focused on designing a binary neural network classifier to distinguish signal from background events. Preliminary results from this show strong promise in enhancing sensitivity across the targeted mass range. Looking ahead, the analysis will be extended to include Run 3 data, with a publication anticipated in 2027. This work not only expands the reach of di-Higgs searches at the LHC but also serves as a testbed for novel machine learning approaches in complex final states involving multiple boosted objects.

2.4.3 Proposed Research: MSSM Higgs Decays to tau pairs

Alharthy, Mettner, Mohammadi, Dasu

For certain regions of parameter space, neutral heavy MSSM Higgs bosons decay preferentially to τ-pairs. The UW team of Bachtis (Ph.D. 2012, CMS Thesis Award, Advisor: Dasu), Ojalvo (Ph.D. 2015, Advisor: Smith), Dodd (Ph.D. 2018, Advisor: Smith) and Ruggles (Ph.D. 2018, Advisor: Dasu), Dr. 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. Alongside the SM Run-3 $H \to \tau\tau$ work discussed earlier, we propose to improve tools and conduct searches for these heavy states with the Run-3 data.

2.4.4 Proposed Research: Searches for new physics in Di-Higgs production

Nelson, Thakore, Pinna, Galloni, Mohammadi, Bose

Our group will continue to play a leading role in high-mass di-Higgs searches, with a particular focus on final states involving tau leptons. These channels offer unique advantages in terms of branching ratios and background suppression, and are especially promising for probing TeV-scale resonances predicted by various BSM scenarios. A central component of our strategy involves the exploration

and deployment of advanced AI/ML techniques to improve the reconstruction and identification of tau leptons—an essential challenge in these analyses.

New graduate student Mitanshu Thakore (Advisor: Prof. Bose) will take over from Parida to lead the Run 3 version of the $X \to HH \to b\bar{b}\tau^+\tau^-$ search. Building on the foundation laid during Run 2, several key improvements are planned. These include the integration of a boosted b-tagger based on Particle Transformers, which offers state-of-the-art performance in identifying merged b-jets, and the development of a semi-resolved event categorization to enhance sensitivity in the critical 1–1.5 TeV mass range, where fully boosted topologies are less dominant. Thakore will also extend the scope of the analysis to investigate scenarios where the heavy resonance X decays into a Standard Model Higgs boson and a new scalar particle $X \to YH$. This direction is motivated by recent hints of excesses in similar searches in other final states (JHEP 05 (2024) 316), and could provide valuable insight into extended Higgs sectors or exotic scalar dynamics.

As previously noted, graduate student Nelson (Advisor: Prof. Bose) is spearheading a pioneering search for new heavy resonances in the $HH \to \tau^+\tau^-\tau^+\tau^-$ final state, utilizing both the Run 2 and Run 3 datasets. This analysis marks the first exploration of the > 1 TeV mass regime in this channel and is expected to yield results that are complementary to other high-mass di-Higgs searches

In parallel, our group will play an active role in the CMS-wide effort to produce a combination paper for high-mass di-Higgs searches using the full Run 2 and Run 3 datasets. This ambitious undertaking involves close coordination across multiple analysis teams to harmonize event selections, categorization strategies, and systematic treatments. The goal is to maximize the sensitivity of the combined result and provide the most comprehensive constraints to date on high mass resonant di-Higgs production at the LHC. Dr. Pinna, who served as co-convener of the CMS B2G Physics Analysis Group (PAG) from 2021 to 2023, will leverage her deep familiarity with the B2G portfolio and its constituent analyses to take a leading role in this collaborative effort. Her experience in navigating the complexities of cross-group coordination will be vital to the effort and together with Dr. Galloni's technical insight into boosted object reconstruction, will be instrumental in ensuring the success of the combination paper.

2.5 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 sufficiently 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 seek evidence for such dark matter particle production by measuring energetic standard model particle recoils from missing energy. Portals to dark matter comprising the Higgs boson or hitherto unknown force particles are also possible. Models of interactions mediated by a new scalar, pseudo-scalar, vector and axial-vector bosons have become popular recently – they are theoretically well-motivated and can be easily accommodated in extended Higgs sectors.

Our group has had leadership roles in this area (Past conveners Dr. Gomber, Dr. Pinna and Dr. Sharma) and have published several DM searches [6, 7, 19, 20, 21, 22, 23, 24, 25]. Dr. Pinna continues to serve as the co-organizer of the LHC-wide Dark Matter Working Group (DMWG) that brings together theorists and experimentalists to define guidelines and recommendations for DM benchmark models and interpretations at the LHC.

2.5.1 Recent Results: Mono-jet and Mono-light-Z' Search

Mallampalli, Sharma, Dasu

Graduate student Mallampalli (Ph.D. 2025, Advisor: Dasu) and Dr. Sharma had searched for mono-jet signature using the full Run-2 data [25] in collaboration with the Boston University group. Stringent constraints obtained on the parameter space of WIMP dark matter and other possible models were published [51]. Mallampalli recently completed a search for a distinctive signature of mono-light-Z' (1-3 GeV) boson production (See Figure 5) [52]. 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 developed machine learning based analysis and produced 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. The analysis was presented in Spring 2025 conferences and is in final stages of journal publication.

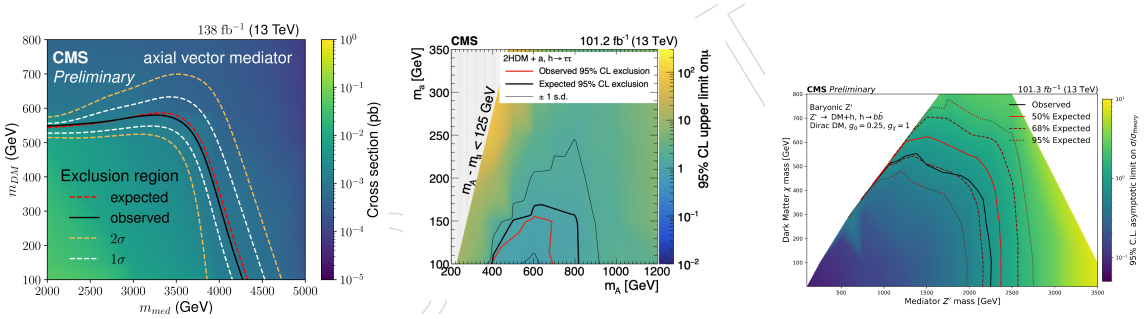

Figure 5: (left) Expected and observed exclusion region in the $m_{DM} - m_{med}$-plane for the axial vector mediator, for $m_{Z'} = 1$ GeV. The color scale represents the theoretical cross section of the signal process. (middle) 95% CL upper limit on the signal strength modifier $\mu = \sigma/\sigma_{theory}$ in $m_a - m_A$ plane. The regions inside the red and black curves correspond to the observed and expected exclusions at 95% CL, respectively.(right) Exclusion limits at 95% CL on the signal strength for the Baryonic-Z' model as a function of $m_{Z'} - m_\chi$. The coupling parameters are fixed to $g_q = 0.25$ and $g_\chi = 1$. The region inside the black (red) contour corresponds to the observed (expected) exclusion. Mediator masses up to 2.1 (2.35) TeV are excluded for a DM mass of 1 GeV. The DM particle masses up to 500 GeV are excluded for a mediator mass of 1.25 TeV.

2.5.2 Recent Results: Mono-Higgs Analyses

Lomte, Sreekala, Sharma, Dasu

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, which are dark matter candidates. Another model uses a baryonic-Z' as mediator. Early results from Run-2 data [7], are recently updated by Dr. Sharma and collaborators using the full Run 2 dataset, in the $H \to \tau\tau$-mode, completing the work reported in the Ph.D. thesis of Jithin Sreekala (Ph.D. 2023, Advisor: Dasu) (See Figure 5) [53]. Graduate student Lomte (Advisor: Dasu) and Dr. Sharma also completed the analysis of resolved and boosted $H \to b\bar{b}$-modes in recoils from large

missing transverse momentum. These results have much higher significance as shown in Figure 5 [54]. Both these analyses were presented in Spring 2025 conferences and are in final stages of publication.

2.5.3 Recent Results: Top + Dark Matter Analyses

Pinna, Shang, Bose

Graduate student Shang (Advisor: Bose) and Dr. Pinna have exploited the full Run-2 dataset for conducting a comprehensive search 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, 55]. 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 recently concluded full Run 2 analysis includes, for the first time, events where two leptons are produced from the decay of the W bosons and is the first search simultaneously optimized for the $t/\bar{t}$+DM and $t\bar{t}$+DM phase spaces across the zero lepton, single-lepton, and two lepton final states. Additional improvements were introduced - for example, new discriminating variables based on the signal topology for dedicated event categorization, use of better performing b-tagging techniques, and a neural network based technique for improving signal optimization in the di-lepton channel. Further improvement in sensitivity stemmed from the higher statistics available in the control regions, where the backgrounds were estimated from data, allowing better constraints on the systematic uncertainties affecting the shape and normalization of the missing transverse momentum spectrum. Overall, the analysis improvements led to results which are better by about 40% with respect to the previous result based on the 2016 dataset. Additionally, Dr. Pinna developed a novel interpretation of the results within the framework of axion-like particle (ALP) models, leading to the first-ever constraints on the coupling of ALPs to top quarks. These results have recently been published in the Journal of High Energy Physics (JHEP) [56].

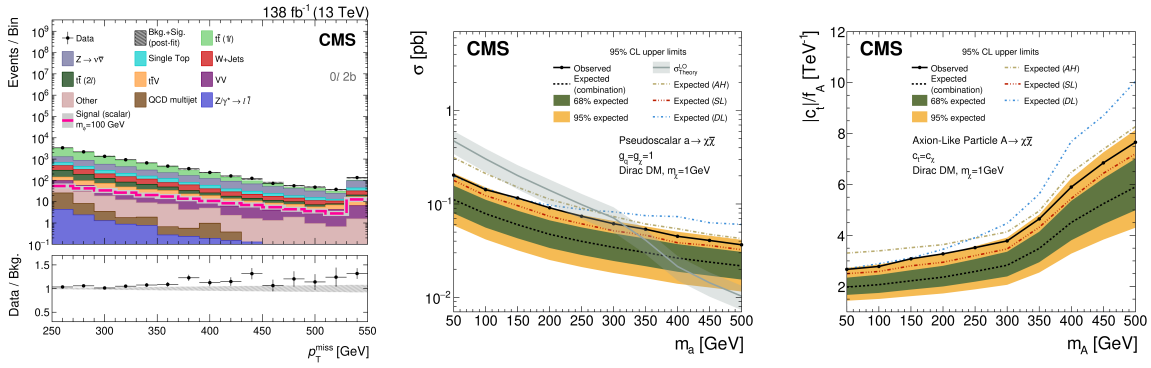

Figure 6: The main discriminant variable, missing transverse momentum, in one of the signal regions of the all-hadronic channel (left). Model-independent 95% CL limits on the production cross section for new physics processes for the pseudoscalar interactions for all three decay channels separately and combined (middle). A slight signal-like excess is observed with local significances between 1.4 and 1.9 standard deviations. The 95% CL limits on the ratio of ALP-top coupling to the ALP decay constant as a function of ALP mediator mass [Pinna, Shang & Bose]

2.5.4 Proposed Research: Dark matter searches

Roderick, Pinna, Sharma, Bose, Dasu

While the main-line analyses based on initial state radiation of high p_T jets, photons, W and Z bosons are planned to be improved with better control of systematic uncertainties, the model dependent searches of mono-Higgs and mono-Z' will also 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. Therefore, the UW dark matter search team proposes to continue this investigation thread.

For the top+DM search, our group will expand the scope of the analysis to include the boosted regime, where high-momentum top quarks are prevalent. Dr. Pinna's phenomenological study indicates that for mediator masses above 1 TeV, nearly 50% of top+DM events fall within this regime, underscoring its importance. To enhance sensitivity in this phase space, new graduate student Jenna Roderick (Advisor: Bose) will develop a dedicated top-tagger capable of identifying both boosted and semi-resolved topologies, thereby strengthening this and related analyses. Additionally, our group will implement novel data-taking strategies, including AI/ML-based approaches, to extend the reach of these searches to lower mediator masses (see Sec. 2.9).

2.6 Searches For Long Lived Particles

2.6.1 Recent Results: Dark matter searches with exotic baryons

Vetens, Black

Graduate student Wren Vetens (Advisor Black) searched 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. 7 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 be 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. The paper is expected to be published in the fall of 2025. Preliminary results are also shown in Fig. 7.

2.6.2 Proposed Research: Dark matter searches with exotic baryons

Verace, Evaraerts, Black

Graduate Student Verace (Advisor: Black) will work to expand and improve the analysis. In particular, the initial data set that was analyzed was limited to the 2018 Run II data. The analysis is statistically limited, and analyzing the full CMS dataset will significantly enhance the sensitivity. A limitation of the current search is that the current analysis limits the search for exotic baryons that interact with the beam pipe. Including interactions that occur in the inner detector will significantly enhance the acceptance for the analysis. The simplified model for the beam pipe interaction will need to be improved by including the much more sophisticated geometry and material map of the entire inner detector in the GEANT simulation. Furthermore, improving the separation of the

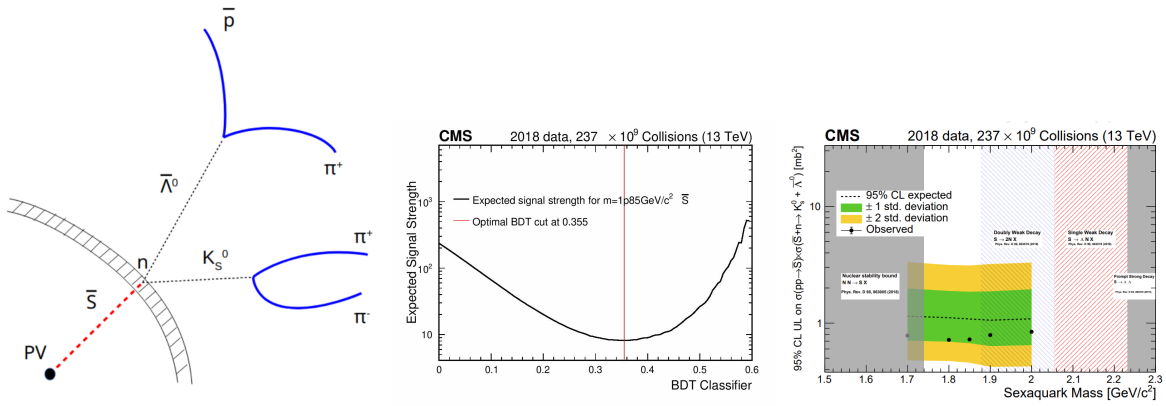

Figure 7: Diagram of the $\bar{S}$ interacting with the beam pipe and subsequent decays (left), optimization of the event selection with a Boosted-Decision Tree (center), preliminary limits as a function of sexaquark mass (right) (Vetens, Black) .

signal and the background with additional machine learning and AI techniques will improve the reach of the search.

2.6.3 Current Research: Search for Displaced Vertices

Warden, Everaerts, Black

Graduate Student Warden (Advisor: Black) works on a physics analysis that searches for long-lived particles via a displaced vertex signature within the beampipe in the CMS experiment, using RPV SUSY as a benchmark model. This exotica search bridges the gap between prompt searches and longer-lived particles that will travel further in the detector before decaying. The analysis strategy is in place, with the requirement that there be one well reconstructed displaced vertex with an associated lepton. A BDT is trained to distinguish background vertices formed from random crossings and signal displaced vertices. For background estimation, an ABCD method is utilized, formed by the orthogonal features: the track multiplicity of the displaced vertex, and the BDT score assigned to the vertex. Only 1-2 background events are expected in the signal region. Preliminary limits without systematic uncertainties show improvements in the $c\tau \leq 20$mm lifetime ranges against other searches for displaced leptons. The performance of the BDT and the limits are shown in 8.

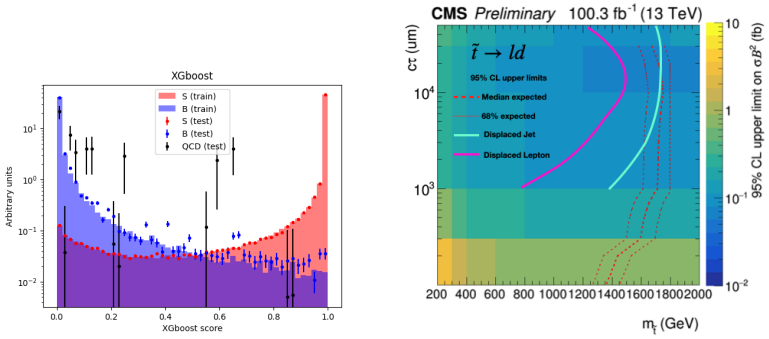

Figure 8: BDT distribution for signal and background for the RPV SUSY search (left), preliminary limits in the mass and lifetime plane (right). (Warden, Everaerts, Black)

New graduate student Cruz (Advisor: Black) will work to improve the analysis by including the entire Run-3 dataset, optimizing the separation between signal and background, and include new decay modes to improve the sensitivity of the analysis.

2.7 Proposed Research: 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. 2.5.3.

Our group has a longstanding history of searches in this area that have resulted in several publications [57, 58, 59, 60, 61, 62, 63] and theses [Victor Shang (Advisor: Bose, PhD 2024), 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). Our expertize and contributions have also been recognized via several leadership positions within CMS, in particular within the context of the CMS B2G Physics Analysis Group (PAG) wherein many of these searches are coordinated. Notably, Charis Koraka serves as Level-3 co-convener of the Very Heavy Fermions subgroup (2023–2025), and Deborah Pinna previously served as Level-2 co-convener of the B2G PAG (2021–2023). These roles underscore our group's active engagement in shaping the direction of new physics searches at the LHC in this area and mentoring the next generation of researchers.

2.7.1 Current Research: Search for triple top quark production with Run 2 data

Teague, Pinna, Black, Bose

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. [64], 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 Dr. Pinna are currently leading a pioneering search for triple top quark production using the full Run 2 dataset - an analysis that has never been performed before at a collider. This analysis has the potential to provide strong constraints for a charged Higgs boson within the 2HDM, while also enabling a first measurement of triple top quark production within the SM. Our group is responsible for analyzing final states with two same-sign leptons or multi-leptons, which are particularly sensitive to the signal and offer strong background rejection.

To enhance the sensitivity of the search, advanced machine learning techniques have been employed, exploiting topological differences between signal and background events. These include classifiers (two-tiered boosted decision tree, BDT) trained to identify the rare triple top topology, as illustrated in Fig. 9. A significant portion of the effort has focused on developing robust background estimation methods, particularly for contributions from fake leptons, which are notoriously difficult to model accurately in simulation. This includes data-driven techniques and control region

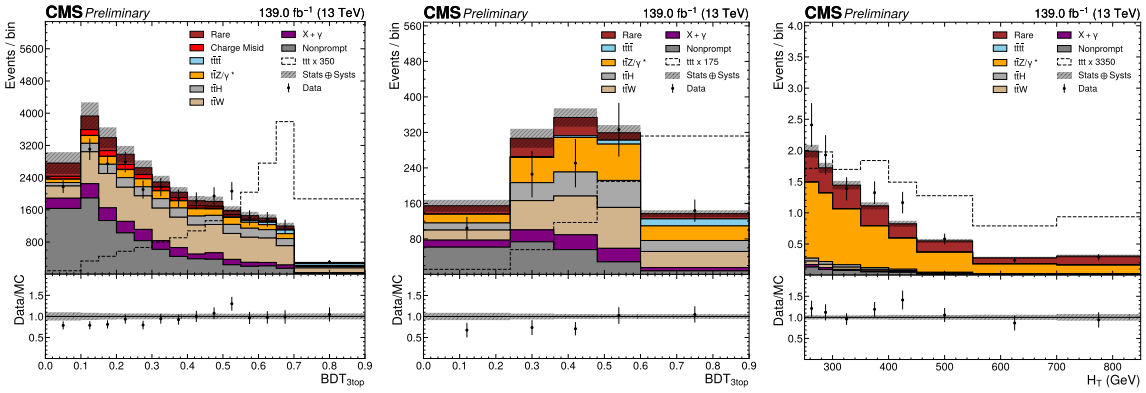

Figure 9: Different input distributions for the triple top quark analysis for the full Run 2 dataset. The plots show the output pf the 3top BDT for the di-lepton channel (left), for the multilepton channel (middle), and the H_T distribution for the ttZ control region (right). (Teague, Pinna, Black, Bose)

validation to ensure reliability and reproducibility. The analysis is currently in the final stages of internal review within CMS and a publication including a combination with the single lepton channel (being performed by Brown University) is expected later this year.

2.7.2 Proposed Research: Search for triple top production with Run 3 data

Sussmane, Pinna, Black, Bose

Given the rarity of triple top quark production, the increased luminosity available during Run 3 presents a valuable opportunity to significantly enhance the sensitivity of this search. Building on the foundation laid by graduate student Teague (Advisor: Black), who is finalizing the Run 2 analysis, graduate student Sussmane (Advisor: Black) will take over and extend the study to include the full Run 3 dataset. This next phase will also incorporate the fully hadronic final state, leveraging our group's prior expertise in other analyses to broaden the reach of the search. A key focus of the Run 3 effort will be the development of improved background estimation techniques, particularly for the challenging fake lepton background, which remains a major source of uncertainty. These methods will be critical for both the leptonic and hadronic channels, and will benefit from advances in machine learning and data-driven modeling.

Beyond its relevance to SM measurements, the triple top quark signature offers a unique window into dark matter production mechanisms, especially in scenarios involving visible decays of new mediators. These processes probe the off-shell regime of spin-0 interactions, a region not currently covered by existing searches. Dr. Pinna will lead efforts to explore this extension, drawing on her expertise in dark matter searches, her leadership role within the LHC Dark Matter Working Group, and interactions with theorists within the LHC DMWG.

2.8 Searches for vector-like leptons

Koraka, Chavez, Bose

Vector-like leptons (VLLs) are electroweak (EW) gauge singlets analogous to vector-like quarks, characterized by left- and right-handed components that transform identically under the EW symmetry group. These particles naturally emerge in a broad spectrum of BSM frameworks, including supersymmetry, theories with extra spatial dimensions, and grand unified models. BSM exten-

sions incorporating one or more families of vector-like fermions can also offer viable dark matter candidates and provide mechanisms to address the observed mass hierarchies among SM fermions through mixing effects. Additionally, VLLs have been proposed as potential explanations for the longstanding discrepancy between the measured and predicted values of the muon's anomalous magnetic moment.

A recent CMS analysis [65], conducted within the framework of the "4321 model" [66, 67, 68], an extension of the SM featuring VLLs, investigated a fully hadronic final state where VLLs decay into b-hadrons and hadronic tau leptons. This study, based on a subset of the Run 2 dataset, reported a modest excess with a local significance of 2.8σ at a VLL mass of 600 GeV, motivating further investigation with larger datasets and different final states.

2.8.1 Current Research: VLL search with Run 2 data

Motivated by the observed excess, postdoc Charis-Kleio Koraka is extending the search for VLLs to the two-lepton final state. To enhance the search sensitivity, she is employing a data-driven technique to estimate the dominant $t\bar{t}$ background. The analysis focuses on final states with zero or one tau lepton and two leptons—either same-sign or opposite-sign—to probe a range of kinematic regions allowed by the "4321 model." This broader strategy aims to improve sensitivity across multiple final states and increase the discovery potential for VLL signals.

Koraka, in collaboration with graduate student Elise Chavez (Advisor: Bose), is integrating advanced machine learning techniques—most notably Deep Neural Networks (DNNs)—to enhance the analysis sensitivity. The framework is built using the Columnar Object Framework for Effective Analysis (coffea), which enables scalable and efficient data processing. The analysis, based on the Run 2 dataset, is currently undergoing internal review within CMS, with a combined publication involving additional final states anticipated later this year. Preliminary results from simulation studies and control regions demonstrate promising performance, underscoring the value of the applied AI/ML methodologies.

2.8.2 Proposed Research: VLL search with Run 3 data

Looking ahead, Koraka and Chavez (Advisor: Bose) plan to extend their analysis to incorporate data from the ongoing LHC Run 3. As part of this effort, they are actively migrating the software pipeline to the latest version of the coffea framework, ensuring compatibility with modern data processing tools and enabling enhanced computational performance. Chavez is also leveraging her collaboration with the Fermilab Elastic Analysis Facility to accelerate time-to-insight and streamline large-scale data workflows. With the increased luminosity of Run 3 and the integration of advanced machine learning techniques—such as Graph Neural Networks (GNNs)—the analysis is expected to achieve significantly improved sensitivity to VLL production.

2.9 Searches with novel data-taking strategies

Our group has strategically leveraged its expertise in detector technologies, trigger systems, and software & computing to pursue a variety of innovative analyses that capitalize on novel data-taking strategies. These include anomaly detection, which enables model-independent searches for rare or unexpected phenomena; data scouting, which allows for the collection of events (with reduced event content) at high rates to probe low-mass regions typically inaccessible with standard triggers; and data parking, which enables the storage of large volumes of data for deferred reconstruction and analysis, thereby maximizing physics reach without overwhelming real-time processing capabilities. By integrating these approaches, we plan to explore new regions of phase space and enhance

sensitivity to potential signals of new physics, while also contributing to the development of scalable, high-throughput analysis pipelines that are essential for Run 3 and beyond.

2.9.1 Proposed Research: Model-independent Run-3 search with anomaly detection

Koraka, Thete, Bose

Postdoc Koraka and new graduate student Ameya Thete (Advisor: Bose) are initiating a Run 3 search for $t\bar{t}$+DM signatures, focusing on hadronic final states. The initial objective is to enhance sensitivity to $t\bar{t}$+DM signals where conventional missing transverse energy (MET)-based triggers have low acceptance. The broader goal is to establish a robust, model-independent framework that can be adapted to probe a wider class of new physics scenarios in the future. To this end, Koraka and Thete are currently evaluating two different strategies. The first leverages the newly integrated anomaly detection triggers at Level-1, accessed via the CMS scouting stream, which enables high-rate data collection with reduced event content. The second strategy utilizes new high-level trigger (HLT) paths available in the CMS parked dataset, which retains full event information but is limited to a subset of the Run 3 data. The expectation is that these strategies would enhance sensitivity to low-mass or low-momentum signatures that the traditional trigger strategy often rejects.

Preliminary trigger studies with the scouting dataset indicate that the anomaly detection strategy significantly improves acceptance for events with low MET and low H_T which are a feature of small dark matter mediator masses. However, this approach requires substantial development to implement key selections—such as MET filters and b-tagging—within the constraints of the reduced event format that is saved. The parking strategy also provides significant gains to sensitivity related to low-mass signatures. Moreover, it supports a conventional analysis workflow with standard object reconstruction. While only available to use for a fraction of the Run 3 dataset, this strategy could potentially utilize anomaly detection at the analysis stage to identify rare topologies.

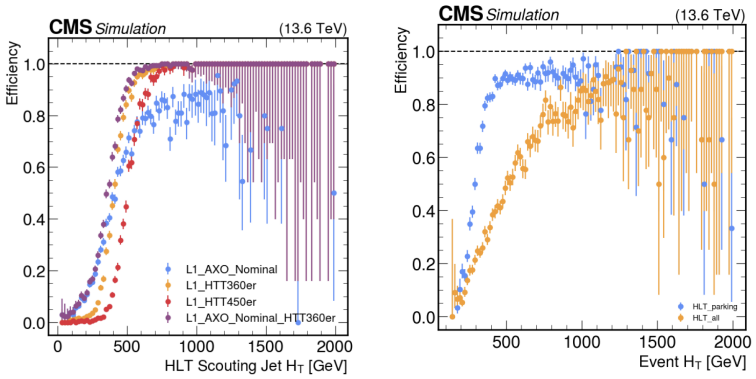

Figure 10: (Left) HLT efficiency shown as a function of the total transverse momentum (H_T) for two different standard L1 H_T paths (yellow, red), for the anomaly detection path (blue), and for their combination (purple) showing a promising increase in acceptance for low values of H_T. (Right) Efficiency for standard HLT triggers (yellow) and parking trigger (blue) as a function of the offline H_T showing substantial gains coming from the parking trigger. [Koraka, Thete, Bose]

Koraka and Thete are currently designing a decision framework to determine the optimal strategy for maximizing sensitivity across different signal hypotheses. Their work will also inform future efforts to integrate machine learning techniques and real-time data selection tools into CMS analyses, contributing to the broader goal of enhancing discovery potential in Run 3 and beyond.

2.10 Searches for new physics with the b-quark

Galloni, Black

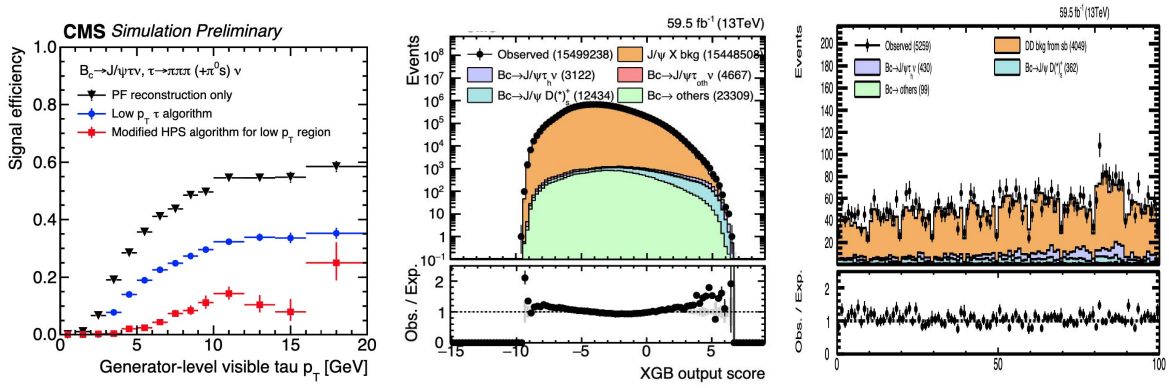

Figure 11: Tau identification efficiency as a function of p_T at the same misidentification rate(left). Multivariate output for signal selection of B meson decays and backgrounds (middle). Distribution of 2018 signal enriched data region of the expected signal and background events in the unrolled two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

Dr. Galloni has performed an analysis probing the flavor universality in B hadron decays [69] using the full Run 2 dataset. 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. In recent years, results from different experiments have 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 by BABAR. BABAR [70, 71], Belle [72, 73, 74, 75] and LHCb [76, 77, 78] show disagreement with SM predictions. A similar $b \to c\ell\nu$ transition can be investigated in the B_c meson decay by measuring the ratio of the branching fractions to $J/\psi\tau\nu_\tau$ and $J/\psi\mu\nu_\mu$.

This ratio is called R(J/ψ), and was first measured by the LHCb collaboration [79]. In fact LHC provides a unique environment to study the B_c meson, as this is not produced in the so-called B-factories that normally operate at energies at the mass of the upsilon meson. Galloni performed this measurement using the CMS data collected between 2016 and 2018, amounting to 138fb^{-1} of integrated luminosity. A boosted decision tree trained with the XGBoost algorithm is trained to distinguished further the signal from the background events, as shown in Fig.12(left), based on kinematical and topological observables in the events, and identify two regions in data, one enriched in signal and one enriched in backgrounds. The background contributions in the signal enriched region are extrapolated from the background enriched region using corrective factors computed from simulations. A distribution of signal and background events for the 2018 data is shown in Fig. 12(center). The measurement is combined with the similar analysis of B_c decay to muons [80], to which Galloni contributed for the computation of trigger efficiency and corrections. The final result is reported in Fig.12(right)and shows a one sigma agreement with both the SM expectations and the previous measurement by the LHCb experiment. The analysis is approved in a PAS [69] and is about to be submitted to the journal.

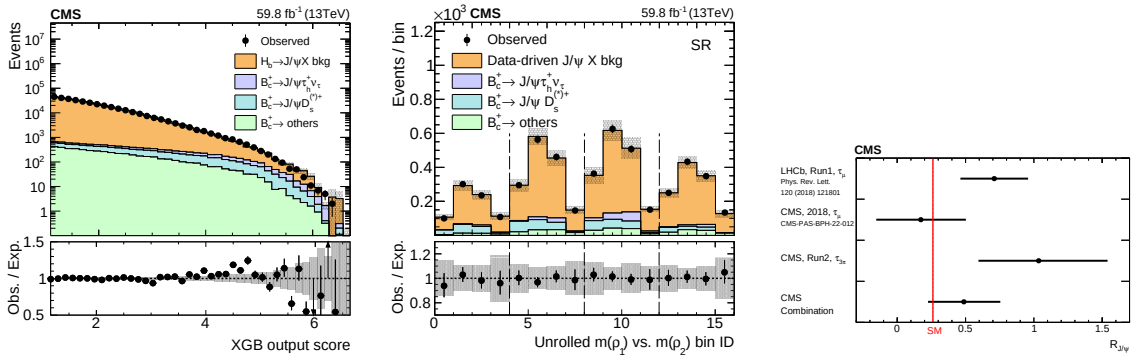

Figure 12: Distributions of the XGBoost discriminator (left) and 2D $\rho(770)$ candidates sliced mass (center) for the 2018 data-taking period. The data (black markers) are compared to the expected yields of the b-hadrons background and simulated B_c processes. On the right, summary of R(J/ψ) measurements. The upper row corresponds to the existing LHCb [79] measurement. The second and third row, respectively, correspond to the CMS analysis using leptonic [80] and hadronic τ decays. The last row represents the combination of the CMS analyses in both final states. The total uncertainties in the measured values are indicated by the horizontal lines. The SM prediction is shown as the vertical red line. (Galloni, Black)

Dr. Galloni developed a new strategy to significantly improve low P_T tau identification for this analysis. Tau leptons decay hadronically with a 65% probability to one or 3 charged pions and, possibly, neutral pions. Especially the decay to 3 charged pions that has a 10% probability is of interest for this analysis because the presence of three tracks coming from a displaced secondary vertex can be use as a handle to discriminate signal and background events [81] now available for all CMS analysis.

2.11 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 [82]. Prof. Black co-led the muon collider forum. Prof. Dasu co-led the electron-positron collider forum. The energy frontier report [83] 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 submitted several white papers to the Snowmass process [84, 85, 86]. 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. Dr. Pinna and Dr. Sharma along with UG students N. Venkatasubramanian and Chen looked at electroweak multiplet WIMP candidate reach at a muon collider. UG student Mettner and Nee (Supervisor: Mohammadi) evaluated beam backgrounds at the C3.

The Particle Physics Project Prioritization Panel (P5), of which Prof. Bose was a member, called for participation in a future off-shore Higgs Factory and development of a 10-TeV pCM collider, potentially sited at FNAL - the muon shot!

Following the P5 report, the UW group is now engaged is end-to-end set of studies of the muon collider. The muon collider represent one of the most important alternatives to reach the 10 TeV

center-of-mass energy scale as it achieves that energy using a reasonably compact collider and with the collision of point like particles. Of particular importance is to make progress in the accelerator front, resulting in a realistic ionization cooling demonstration. Forming a new collaboration with FNAL accelerator scientists we are engaged in developing MC demonstrator designs. Prof Black served as the IMCC european studies group paper submission editor [87]. Profs Black and Dasu serve in the USMCC and IMCC management team.

Graduate students Nee and Alharthy are studying the the production target to optimize muon production. Both Nee and Alharthy are already able to present their work in poster sessions of conferences and workshops. They will get trained in experimental aspects of HEP in their accelerator work, while also performing physics studies using the CMS data for their Ph.D. theses. Undergraduate Prateek Rao is studying the muon capture solenoid chicane. Undergraduate Maina is studying muon ionization cooling. Undergraduates Kianian and Glassman are studying tau finding in the MAIA detector. Profs. Black, Dasu and Herndon along with Dr. Mohammadi supervise these studies.

2.12 Physics Analyses Service

Profs. Black, Bose, Dasu, and Herndon, and Drs. Savin, Everaerts, Pinna, Sharma, Koraka, and distinguished emeritus scientist Dr. 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 and Prof. Herndon serves as a member of the SM publication committee and will take over as chair in September. Prof. Herndon performs the job of organizing the Wisconsin review for papers assigned for our Institutional Review in the publication process.

2.13 Fermilab LPC Activities

Prof. Black was LPC co-coordinator from 2020-2024 and played the important role of bringing the US CMS LHC community to collaborate together at Fermilab. Dr. Pinna (2022-2023) and Prof. Dasu were selected as LPC Distinguished Researchers. 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 and collaborates with LPC scientists on physics analyses and software and computing projects. Prof Black now serves on the LPC Management Board.

3 CMS Trigger Activity

3.1 Trigger Overview and Responsibilities

The CMS Trigger System [88] was architected by the UW trigger group under the leadership of Prof. Smith, APS Panofsky Prize winner for this work, and Prof. Dasu in mid 1990s. 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 [89], 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.

The Wisconsin group continues to be 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 FPGA-based L1T for the HL-LHC [90] (2) Planning and execution of HL-LHC HLT algorithm and technical improvements with GPUs, both including the use of AI/ML.

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 oversaw the commissioning of the CMS HLT during Run 1 and Run 2, and served as CMS Trigger Coordinator from 2014 to 2016. Her research continues to center on the HLT system and its physics performance, with her team actively developing GPU-based HLT algorithms and overseeing GPU-enabled HLT operations. In her current role as CMS Heterogeneous Computing Officer within the CMS Offline & Computing organization, Prof. Bose coordinates closely with the HLT group to ensure seamless integration of heterogeneous computing strategies into offline software development and operations.

Dr. 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. Dr. Sharma has resumed his role as the L1T Technical Co-coordinator for a second term recently. Both Savin and Sharma are partly supported by the US CMS project in recognition of their important roles in L1T.

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). The CTP7 uses a Virtex-7 FPGA, a ZYNQ System-on-Chip (SoC) running embedded Linux, multi-gigabit (up to 10 Gb/s) input/output on optical fibers. 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. Dr. Sharma serves as the L1T technical coordinator. The graduate students, currently Simeon and Princeton students, work with Dr. Savin and Dr. Sharma onsite, providing on-call service, calibrations, and making any necessary software

updates. Since the trigger is a critical item for CMS during running, at least one UW expert is on call 24 hours a day.

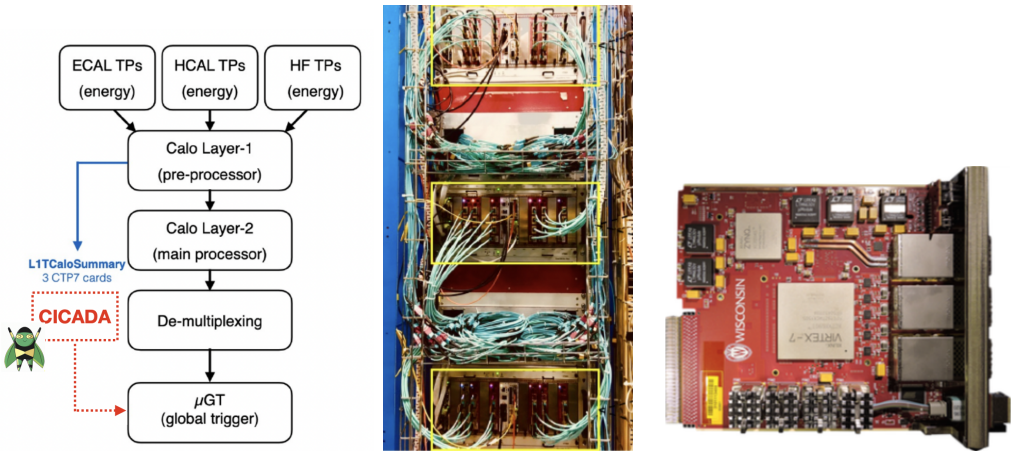

Figure 13: L1T calorimeter trigger system with the new CICADA addition (left). Layer-1 installation in Point 5 with three uTCA crates with CTP7s (middle). CTP7 Board (right).

3.3 CICADA - Machine Learning in FPGAs

Probing the remaining parameter space using Run-3 data often involves production of multiple soft particles in the final state, presenting a major level-1 trigger challenge, requiring multi-object event-level correlations. During the long shutdown Wisconsin and Princeton groups worked together to build new capabilities based on machine learning for across-the-board improvement. This ML system called Calorimeter Image Convolutional Anomaly Detection Algorithm (CICADA), provides a model-agnostic trigger for new physics, removing bias towards any particular physics model. Graduate Student Tsoi (Ph.D. 2024, Best CMS Thesis Award, Advisor: Dasu) has used ML techniques in collaboration with Princeton and MIT groups to develop suitable firmware for CTP7s[91]. The ML algorithm's large resource utilization is mitigated using Knowledge Distillation and Weights Quantization techniques to implement on FPGAs with HLS4ML software package. Dr. Sharma and Dr. Savin, working with Wisconsin and Princeton engineers, deployed CICADA trigger firmware in Run-3 trigger system, using an additional set of Wisconsin built CTP7 μTCA cards in each crate and taking advantage of the backplane links connecting the cards (See Figure 13).

CICADA level-1 trigger provides higher efficiency for a plethora of physics processes involving production of correlated low E_T clusters. Tsoi's 2025 best thesis award was in recognition of this ML work for trigger system and analysis tool improvements. The improvements in performance of the trigger system with these additions are shown in Figure 14.

3.4 HL-LHC Trigger System

For the HL-LHC running, planned to start in 2030, 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 [90]. The overhauled trigger system block diagram is shown in the Figure 15. The experienced UW electronics engineering team led by Tom

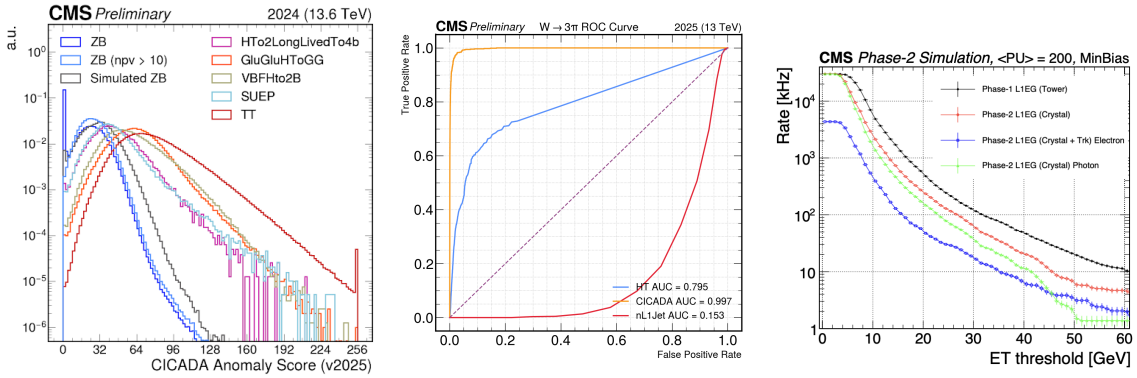

Figure 14: CICADA score for zerobias background and several physics processes (left). ROC curve for $W \to 3\pi$ showing improved CICADA performance (middle) Improvement in rate reduction for electron and photon triggers using crystal data and L1 tracks in HL-LHC trigger (right).

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 34-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 Dr. Savin in 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.

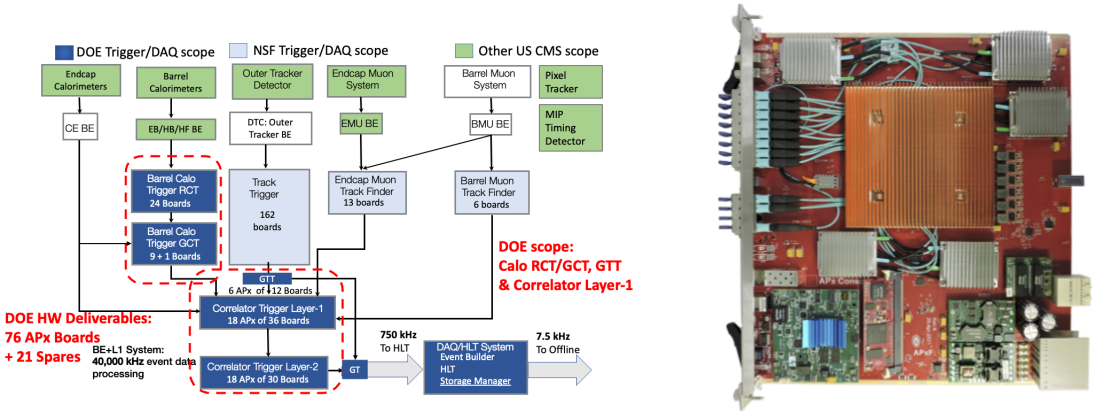

Figure 15: The HL-LHC Trigger System showing the UW hardware responsibility (left). The APxF ATCA board built by the UW group (right).

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 Dr. Savin, Dr. Sharma, graduate student Simeon and others from Princeton and Hyderabad, are working on the HL-LHC Calorimeter Trigger Upgrade algorithms, inluding some AI/ML variants. 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.

3.5 High Level Trigger

Our group has played a leading role in CMS HLT development and operations since the start of Run 1. Prof. Bose served as the Deputy Trigger Coordinator (2011-2012) and later as the CMS Trigger Co-coordinator (2014-2016). Dr. Pinna contributed significantly as the L2-convener of the STEAM (Strategy, Trigger Evolution & Monitoring) group within the Trigger Studies Group (TSG) from 2020-2021. In this role, Dr. Pinna collaborated with all CMS physics groups to design and monitor trigger menus, including performance metrics such as rates, timing, and efficiencies. Her leadership helped lower the barrier for physics groups to engage in trigger studies via the organization of key tutorials such as HATS 2021 and the CMS DAS Trigger exercises (2022, 2023). These efforts were instrumental in preparing trigger menus for Run 3 data-taking.

3.5.1 HLT Algorithm Development, Performance Studies & GPU Integration

Our group members have made significant contributions to HLT algorithm development and performance optimization. Former graduate student D. Rankin (Advisor: Bose, PhD. 2018) 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, PhD. 2018) was responsible for evaluating and monitoring the CPU performance of all HLT algorithms. Continuing this tradition, graduate student Parida (Advisor: Bose) played a key role in rate measurements for Run 3 trigger menus and in the transition to GPU-based HLT operations [92]. With the integration of GPUs into the CMS HLT farm for Run 3, Parida conducted detailed performance studies comparing CPU and GPU triggers, identifying and resolving several issues in the new GPU codebase—contributions that were critical to the success of Run 3 data-taking.

Postdoc Koraka is playing a critical role in CMS's adoption of GPU-based computing. As L3 convener for GPU-based Offline Reconstruction within CMS Offline & Computing, she co-

organizes (with the HLT group) the GPU development forum and oversees cross-domain GPU efforts. Additionally, together with graduate student Nelson (Advisor: Bose), she is porting the electron pixel matching algorithm used in CMS E/gamma reconstruction to GPUs, with the aim of accelerating the most computationally intensive step of the electron reconstruction algorithm. Using the Alpaka performance portability library, the group has developed and validated a GPU-based seeding prototype, with preliminary results presented at CHEP 2024 [93],[94]. Dr. Koraka and graduate student Shang (Advisor: Bose) have also served as TOP PAG trigger conveners, overseeing trigger path monitoring, efficiency measurements, and performance studies to ensure high data quality and early issue detection. They also reviewed TOP PAG analyses for proper trigger usage and scale factor application.

3.5.2 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 Trigger Coordination(2013-2015). Former graduate students Clint Richardson and Dylan Rankin were active members of FOG and served as HLT on-call experts. More recently, student Parida served as an HLT Detector-On-Call (DOC) expert during Run 3 (2022-2024) and was part of a small team of CMS-wide experts providing immediate 24/7 support for any HLT operations issue. Student Nelson took over this responsibility starting in 2025.

3.5.3 HLT Plans for Run 3 and beyond

Dr. Koraka and student Nelson will complete the GPU porting of the E/gamma reconstruction algorithm. focusing on improving physics performance for low-momentum electrons and integrating the algorithm into CMS's central software framework. Their goal is to deploy this online during the 2026 run. This work aligns with our broader efforts in Software & Computing (S&C) and leverages GPU resources at our Tier-2 center and the Center for High Throughput Computing (CHTC) at UW–Madison. Nelson will continue to study and validate GPU versions of new HLT code and serve as an HLT DOC while stationed at CERN. Looking ahead to HL-LHC, our group plans to participate in HLT algorithm and menu development with a focus on designing and offloading GPU-based algorithms.

4 Muon System Activities

Led by Professors Herndon and Black the UW muon group is active, respectively, in Cathode Strip Chamber (CSC) and Gas Electron Multiplier (GEM) operations, data quality monitoring (DQM), backend electronics upgrade, and muon group leadership.

4.1 Cathode Strip Chamber System Activities

The UW role in the CMS Muon system project includes leadership in the Cathode Strip Chamber (CSC) forward muon system and responsibilities for chamber mechanics, operations, monitoring, and performance analysis. During LS3 the UW CSC group will take a leading role in LS3 planning and execution which includes the dismounting, re-installation and re-commissioning of the CSC chambers on the the first CSC disks (YE1s). Prof. Herndon leads the UW CSC program, supervising former Dr. De Bruyn (now at the Universite Libre de Bruxelles since 2024), Dr. Galloni (50% CSC, 50% GEM), and graduate students He, Mondal, Marquez, and Austin.

Prof. Herndon serves as CSC resource manager, responsible for person power and budgets for the international CSC collaboration. Also Prof. Herndon serves as USCMS L2 deputy EMU operations manager with similar responsibilities for US contribution to operations of both the CSC and GEM detectors. During this period of time these positions involved substantial planning to manage the impact of the cessation Russian Federation involvement at CERN which led to the PNPI and Tomsk institutions leaving the CSC project. This transition involved the assumption of projects including the completion of a CSC HV system upgrade and key operational and maintenance activities by US institutions. In both of these roles Prof. Herndon assisted in navigating these challenges and ensuring the continued safe and efficient operation of the CSC detector. Currently these positions entail managing operations budgets and personnel for the ongoing Run 3 and planning for all EMU activities during LS3.

Also 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.

4.1.1 Run 3

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 as deputy and then primary Upgrade coordinator, CMS entered the Run 3 data taking period in 2023. During the first year of Run 3, Dr. De Bruyn, then serving 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, Mondal and Marquez served as DOCs during the period 2023-2025, 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.

4.1.2 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. The detector performance studies are focused on using tag and probe (T&P) method studies of Z decays to muons to understand hit and segment reconstruction and trigger primitive (LCT) efficiencies [95]. Previously Prof. Herndon redesigned the T&P to enable analysis of the full T&P nTuple data, typically tens of millions of Z candidate events, on times scales of less than an hour in order to enable and iterate complex studies on short time scales. In addition, graduate student Marquez automated all portions of the data processing, for production of nTuples, and efficiency analysis of the nTuple data. These improvements made it possibly to quickly process the order $100 fb^{-1}$ sized datasets of Run 3 to perform high statistics efficiencies studies using the full Run 3 data set or provide feedback on performance using smaller datasets on the time scale of days, typically limited only by the time to collect and centrally reconstruct enough data to perform an efficiency evaluation. The 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, as function of time, and as function of instantaneous luminosity (number of primary vertices). One feature of the automation of the efficiency analysis stage designed by Marquez is an automatic cataloging of all significant sources of efficiency loss at the level of individual chamber readout chips and as a function of time. This is essential given the complexity of the CSC system in terms of the number of chambers and readout chips. Given the ability to quickly identify problems this software has been

used to identify and characterize efficiency issues with sufficient detail to allow the operations group to fix problems and then also provide quick feedback on the effectiveness of attempted interventions. Examples include the identification of the OOS (out of sync) readout issue in the ME1X rings with led to inefficiencies as large as 25% at the highest luminosity and the identification of cases where the LCT efficiency was order 10% lower than offline segment efficiencies due to incorrect BX timing parameters. In both cases the UW group tag and probe efficiency analysis was used to initially identify the efficiency issue and to evaluate the system performance after fixes were designed. Figure 16 (right) shows an example of the efficiency vs the number of primary vertices in the 2nd, 3rd and 4th stations of the CSC system. This plot was generated after deploying new firmware to address the OOS readout issue, demonstrating, within a week of the LHC reading sufficient luminosity, that the new firmware reduced any inefficiency at high instantaneous luminosity to a fraction of a percent. Plots subtracting segment and trigger, local CSC track (LCT), efficiencies were used to visualize the issue where segment efficiencies systematically exceeded LCT efficiencies Figure 16 (left) confirms the resolution of the problem by correcting BX timing problems. The issue was initially identified by an automatic checks that compare segment and LCT efficiencies run as part of the UW tag and probe analysis. Muon reconstruction efficiency, trigger efficiency, detector time and space resolution have been stable and high quality throughout Run 3 and the efficiency monitoring provided by the UW group has been a key element in maintaining this performance.

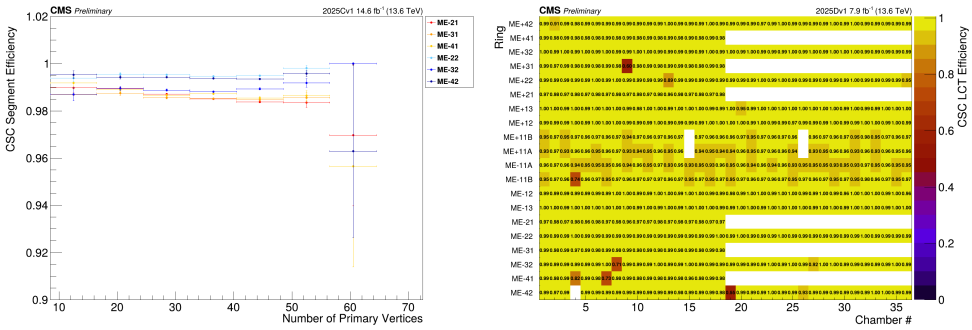

Figure 16: MEX1 Out of Sync problem fully solved in by new firmware. Any remaining inefficiency as a function of instantaneous luminosity (using number of primary vertices as a proxy) is reduced to a fraction of a percent (left). A new problem where segment efficiencies were higher than trigger (LCT) efficiencies was found in several chambers in the 2025C data. A 10% efficiency loss effected chambers ME+1/3/10 and 30, ME-1/3/10, ME-2/2/1, ME-3/2/30 and was first identified by automated checks programmed by graduate student Marquez. The problem was due to incorrect bunch cross timing constants and was fixed in the next running period, 2025D (right). The remaining issues are generally due to known single readout chip or chamber failures.

Continuing work started in 2024 graduate student Austin has completed an adaptation of the reconstruction and nTuple generation phase of the tag and probe analysis using nanaAOD data access and storage techniques. The adaptation, within the framework of the muon detector performance groups DPG nTuple, minimized the use of lower level raw data quantities and allows processing of the reconstructed data into nTuple for efficiency analysis in times scales slightly more than four times faster that the current system. This reduces the time to generate of nTuples, which typically took older 1-2 days, to order 6-12 hours. This will make it possible to process large data sets more quickly and even reprocess data sets introducing new variables to the nTuple, which will be necessary to cope with HL-LHC sized datasets and offer quick response to operations issues.

Mr. Austin is now working on an adaptation of the nTuple level efficiency analysis to use the new nTuple format. Once completed this framework will be used for new studies of system performance investigating issues like BX timing, correlation of efficiency effects and fluence through the detector, efficiency vs high voltage distribution sectors and during Run 4.

4.1.3 CSC Background rate and composition studies and MC generation

In addition the CMS muon group completed a detailed study of backgrounds in the CMS muon detector [96] including work by He to study background rates in data and MC and Long to study background rates at high radiation fluence and dark rates. Prof. Herndon expects to further leverage this work with Marquez to understand possible optimizations in MC production of the amount of out of time signal and background information kept in the MC which has significant storage and time implications for HL-LHC MC production. Ideas to optimize this process include optimizing the amount of data stored based on detailed understanding of the background sources in the muon system, on the fly background hit production, since CPU is less constrained than storage, and applying machine learning techniques to achieve "parameterized" background generation.

4.1.4 LS3

In 2026 the LHC will complete Run 3 and begin long shutdown 3 (LS3). During LS3 all CSC chambers on the first disks (YE1s) will be dismounted to make room for the high granularity calorimeter (HGCal) installation. The UW group will participate in this task contributing personnel and extensive experience. During LS2, when the front-end electronics of the most forward parts of the CSCs were upgraded, the UW group participated in chamber removal, refurbishment, testing, installation and re-commissioning. Also the UW group, working with the UW physical science laboratory) designed the mechanical fixtures that remove chambers and for the upcoming shutdown are designing new transporters to move the chambers after dismounting them from the disks. During LS3, three rings of CSC chamber on each side of the detector will be dismounted, taken to building 904 for interventions to fix problems and storage, then returned, reinstalled, and re-commissioned. In addition, the services of the innermost CSC rings ME1 will be replaced. During this period Dr. Galloni and UW students will participate in the full program of on site activities involving the YE1 CSC chambers. Specifically Dr. Galloni will participate in chamber removal and installation activities which UW scientists also participated in during Run 2.

In his roles as CSC RMO and USCMS L2 EMU operations deputy manager Prof. Herndon is responsible for the budget and person-power planning of the full 2026-2030 LS3 periods. This requires understanding the schedule of LS3 planned at the level of days and working with the international CSC institutions and the US institutions to ensure that the necessary person power is available on site to perform all tasks. The budget planning includes the budgets for materials and personnel necessary to accomplish the LS3 program.

4.1.5 Synergistic activities with GEM

In addition, with Dr. Galloni, Prof. Herndon and his students are working on efficiency studies involving both the CSC and GEM. A future direction for this work is to integrate the GEM and CSC efficiency studies to both understand the joint performance of the system and enhance the overall diagnostic ability of the current UW tag and probe framework. Additionally, Dr. Pinna is working in the area of GEM trigger primitive algorithm optimization. The integrated monitoring will access performance for both trigger primitives and offline reconstruction of CSC and GEM

hits and segments. The UW group intends to leverage our experience gained in the GEM electronics, firmware, software 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 end-cap region, integrated monitoring is essential for guaranteeing the performance of the upgraded EMU system.

4.1.6 Summary of CSC activities

In summary, the UW group will play a major role in both in activities during the upcoming shutdown and in maintaining the highest CSC detector efficiencies in order to generate high quality data to be used in physics analyses throughout the lifetime of the experiment. Our participation in these activities will train the next-generation UW students and post-docs in the UW institutional responsibilities including: detector operation, detector infrastructure, on-call detector experts, data quality monitoring and detector performance studies.

4.2 Gas Electron Multiplier Chambers (GEMS)

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 are composed of 3 types of detectors, ME0, GE1/1, and GE2/1, that are installed or foreseen in the CMS experiment in the forward region along the beam pipe at 5.3m, 5.7m, and 8m from the interaction point. The GE1/1 detectors were installed during the second LHC Long Shutdown (2019-2021) in the end-cap muon system of CMS and are taking data in the LHC Run 3 (2022-2026). Additional GE2/1 layers were installed in the second muon station in preparation for HL-LHC running. The GEM detectors will add redundancy to the muon system in the $1.6 \leq |\eta| \leq 2.1$ region, where the end-cap muon system had the fewest number of layers but the highest background rate. In addition, the GEM ME0 detectors will increase the acceptance of the system out to $|\eta| \leq 2.9$ 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 2018. The US scope of the project includes approximately half of the readout electronics, focusing on the back-end electronics for the 3 GEM stations. From 2019-2020 Prof Black was the GEM run-coordinator.From 2020-2023, Prof. Black was the GEM project electronics coordinator for international CMS. Additionally, Prof. Black was appointed as the GEM review coordinator for all GEM activities in the international CMS since 2018. Since, 2024 Prof. Black has been the GEM IB chair. The scope of the US project includes the OpticalHybrid (OH) boards that collect and process data from the front-end ASICs (VFAT3s), the optical links, and the back-end system (baed on the uTCA standard for Run 3 and the ATCA standard for HL-LHC) which then sends the data to the L1 endcap muon trigger system and central CMS data acquisition system. 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 works on the development and implementation of the stub-finding algorithm for the ME0 detector.

Since 2019, as then postdoc and now Scientist, Galloni has joined the GEM data acquisition software and firmware team, becoming its leader in 2020. Under her supervision, the GEM software was extended and integrated with the rest of the CMS software. From 2020, she led the effort of the

commissioning of the GE1/1 detector during and after the installation, ensuring reliable and good detector performance. Since 2021, she has been the L3 Run Coordinator for GEM, managing the team in charge of the operations of the GE1/1 and GE2/1 chambers installed in the CMS detector and providing training for experts and shifters on call.

Since 2020, Dr. Everaerts has led the integration effort at CERN, testing the electronics on the CERN test stands and for the construction of the GE2/1 and ME0 detectors. He held the position of L3 integration manager, deputy project manager, and has recently been appointed as the next GEM project manager, starting in September 2025. Dr. Everaerts has also set up 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 before the installation in the CMS detector. Recently he has taken the lead of the lab at CERN for the final assembly and testing of the ME0 detector stacks.

Since 2023, Dr. Pétré (Advisor: Black, supported by operations) has been in charge of the GEM online software and firmware for the front-end and the back-end boards of the data acquisition system. He developed the architecture of the current GEM DAQ software, ensuring its scalability from a test stand with just a few chambers to the complete detector made out of the GE1/1, GE2/1, and ME0 stations, totalling hundreds of detectors. The DAQ system has been able to reliably take GEM data with the best achievable performance and to operate seamlessly within the rest of the CMS experiment and data acquisition system. Dr. Pétré works closely with Dr. Galloni and Dr. Everearts to make sure all the specifications for GE1/1 and the future generation detectors are kept in mind while developing software and firmware. Since 2005, Dr. Pinna has begun working on optimizing the readout to reduce noise as well as improving the L1 GEM trigger primitives.

4.2.1 GEM Data Acquisition System

Dr. Pétré and Dr. Galloni are the main developers GEM online software, which controls and monitors the data acquisition and calibration routines of the GEM detector. Pétré oversees the development and is responsible for the core features, whereas Galloni focuses on the so-called calibration suite, which performs the calibration scans necessary for the correct configuration of the electronics to ensure good performance, as well as health assessment during sustained operations. Another central feature of the online software was worked on by PhD Student Teague (Advisor: Black) until 2023: the amelioration of the monitoring suite, which is of crucial importance while taking data, to ensure that the hardware, event building, and trigger are fully functional. As a result, the GEM DAQ operations have been smooth with limited downtime attributed to GEM since the beginning of Run 3. Part of this success is also due to DAQ expert on-call shifts, covered by Pétré and Galloni.

Since 2020, the UW group has been actively involved in the redesign of the GEM online software. From a collection of routines used for the quality control during production and a prototype for the data taking with just a few chambers during the GE1/1 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 the ME0 and GE2/1 stations. Of particular importance is the requirement to handle seamlessly the communication instabilities with the front-end, mainly due to the VTRx transceivers' out-gassing. This includes improving the robustness of the calibration routines to best tune the GEx/1 detector electronics. Most recently, in 2024, Dr. Pétré implemented an innovative method in the online software, with the participation of the backend firmware, to identify and reprogram FPGA affected by Single Event Upsets (SEUs) transparently in the background of an ongoing CMS run.

Since 2021, Dr. Galloni and PhD student Aravind have been involved in the development

and optimization of the VFAT calibration scan analysis routines, targeting the optimization of the analogue front-end biasing circuits (DAC) as well as the reliable detection of damages to the electronics due to high-voltage discharges occurring in the GEM detector. This tool proved essential to assess the health of the detector, refine its operation mode, and plan for eventual repairs.

Moreover, Dr. Pétré is active in the GEM FPGA firmware development. He is responsible for the development of the firmware of the FPGA embedded on the GE1/1 and GE2/1 OptoHybrid boards. The firmware's main task consists of the compression of 61 Gbps signals coming from the VFATs in order to generate Level-1 Trigger Primitives (TPs) at 6.4 Gbps. He also maintains the back-end firmware releases used in operations for data-taking.

The UW group expects to remain a key player in the GEM DAQ system by (1) maintaining the online software, improving its compatibility with the new ME0 and GE2/1 stations as well as the new back-end boards based on the ATCA standard (X2O boards), (2) pursuing the FPGA firmware development efforts, focusing on HL-LHC requirements, both for the OptoHybrid and back-end board, (3) and continuously refining the DAQ tools following the feedback from its users.

4.2.2 GEM Operations

Prof. Black was CMS Deputy GEM Run Coordinator between 2019-2020 and worked to organize and oversee the commissioning of the GEM detectors and operations. From 2021 to present, Dr. Galloni has been the GEM Run Coordinator. One of her critical responsibilities during data taking is to ensure the usage of the ideal electronics configuration settings, which optimize the detection efficiency and timing. Galloni also trains and supervises all GEM shifters during operations and data taking. She has been helped by PhD students Warden (Advisor: Black) and Aravind (Advisor: Black) , which participated in the operations activities with weekly detector and on-call shifts for the GEM detector. Dr. Pétré participates to the effort as GEM DAQ expert on call.

In 2023 and 2024, Dr. Galloni and Dr. Pétré established an automated framework to promptly (less than 72 hours) measure the GEM detection efficiency with large statistics. Starting from the RPCMonitor dataset, a dataset that includes only the raw data from the CMS muon detectors, a software framework was developed to analyse the data as soon as it is available for processing at the Tier-0, to perform the muon track reconstruction, and to associate hits in the GEM detector with those said muon tracks. This tool was of vital importance during the detector commissioning phase, and is still used daily to monitor the performance of the detector and ensure of the correct operating conditions During the commissioning phase, several readout electronics parameters were tested: the VFAT amplifier gain, the VFAT comparator modes, and the high-voltage working point, as shown in Fig18. The prompt feedback brought by the automation helped in steering the optimization in the most promising direction. At the end of this optimization procedure, Dr. Galloni could establish the most effective HV settings while taking into consideration the risk of HV discharges. With the updated settings, the efficiency of the correctly operating part of the detector was measured to be 94% with a total gain with respect to the initial settings of the detector at the beginning of 2024 was of roughly 7% as shown in Fig 17.

During LS3, it is foreseen that the normal operations activity will convert to commissioning of the ME0 and GE1/1 detectors that will be installed on the surface and in the CSM cavern from 2027, building on the experience of the GE1/1 installation during LS2. This will mean providing the setup and the software for data acquisition and detector characterization during the installation, and instructing the commissioning team to obtain good and reliable performance.

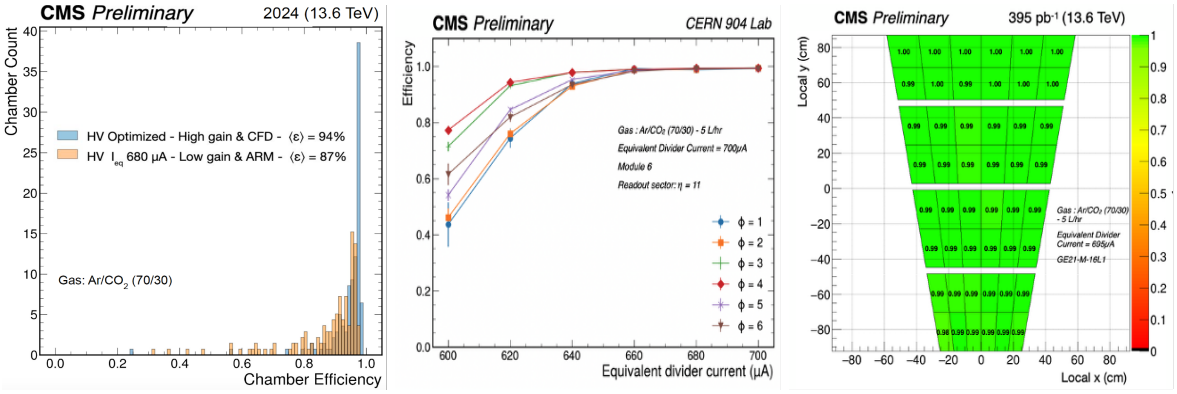

Figure 17: Efficiency of the GE11 detector before and after the optimization procedure in 2024. [97].GE21 detector efficiency measured during the production and after the chamber installation in CMS during the end of the year technical stop in 23-24. (center and right)[98]

4.2.3 GEM L1 Trigger

The UW group is involved in the integration of GEM into the CMS Level-1 Trigger (L1T), thus in the improvement of the quality of the GE1/1 (and GE2/1) trigger primitives (TPs).

One of the main focuses in 2024 was the timing studies of the GE1/1 TPs. It had been shown on an ME0 prototype the possibility of reaching a time resolution of 11ns with an optimized front-end configuration and offline post-processing: early cross-talk signals induced on strips adjacent to the genuine signal smear the time resolution and must be removed. Based on this, Dr. Pétré (Advisor: Black) prototyped and implemented in the GE1/1 and GE2/1 OptoHybrid firmware a pre-processing algorithm to keep only the in-time signal. This new firmware was tested and then fully deployed in September 2024 in the whole GEM system. As a result, the most probable value of the time resolution drastically improved from 16ns (blue in 18) to 12ns (red in 18). Benefiting from the enhanced GEM timing, fine calibration of the delays between the GEM TPs and the CSC OTMB ALCT was performed in September 2024, checking the effects on the matching efficiency and the time resolution.

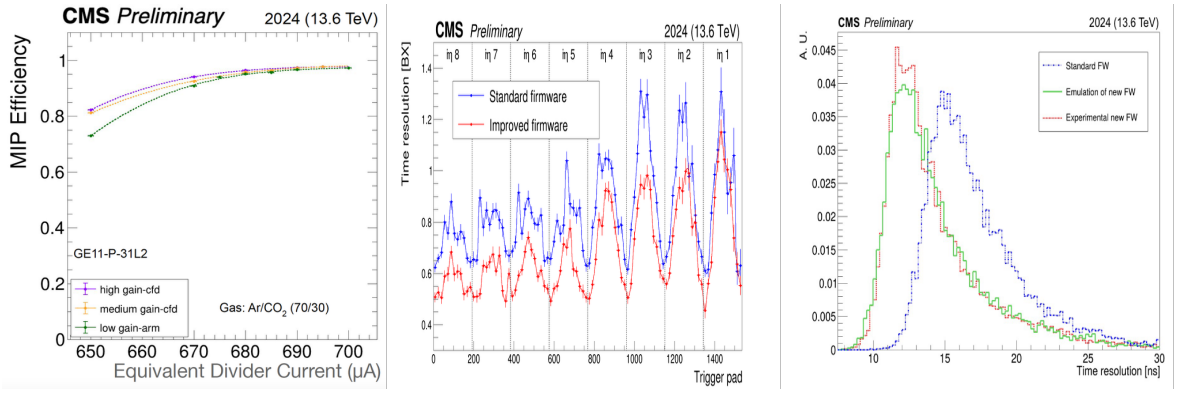

Figure 18: Efficiency as a function of the High voltage settings and the front-end parameters concerning the gain of the pre-amplifier and the comparator mode for the GE11-P-31L2 chamber. [97]Time resolution of the GE11 Trigger primitives. [99] (center), Time resolution before (blue) and after (red) the firmware improvements. [100] .

The integration of GE1/1 into the L1T via the OTMB path was finally completed in October 2024 by using the GEM TPs in the calculation of the muon segment slope within the OTMB algorithm, before sending the enhanced LCT to the CMS Level-1 muon trigger. This marked the completion of a major milestone for the GEM project. From 2025, Dr. Pétré has been involved in the integration of the GEM directly with the CMS L1 muon trigger, starting with the time alignment and initial performance checks. Once the initial integration is completed in both paths, the focus will shift to optimizing the trigger capabilities and algorithms of the GEx/1 stations. In particular, the longer L1T latency in the HL-LHC system will allow the UW GEM group to further refine the algorithms and enhance the TP timing, efficiency, and noise rejection features.

In order, amongst others, to support the Level-1 Trigger development and testing, the so-called integration area at CERN has been undergoing a complete refurbishment by the GEM (Pétré, Galloni) and CSC groups in the years 2023-2024. The final goal is to reach production-like systems for both GEx/1 and ME0, together with their CSC companion chambers, with the possibility to accomplish both single subsystem developments and common integration. This setup will keep being maintained and used by the UW group. Dr. Pinna will work on the optimization of the trigger primitives generated by the GEx/1, ME0, CMS backend electronics to optimize the efficiency in high pileup backgrounds. The current algorithm which is implemented in the firmware builds simple projective roads for ME0 and adds GEx/1 hits to segments found in the corresponding CSC Chambers. Dr. Pinna will study the efficiency and fake rate of multivariate AI inspired models of segment finding to improve the trigger efficiency and rates for the GEMs.

4.2.4 GEM HL-LHC Upgrade

The final validation of the GE2/1 chambers was meant to happen during the QC8 step at CERN using a medium-scale (up to 6 chambers) cosmic ray hodoscope, following testing procedures established by Dr. Everaerts with PhD Student Warden (Advisor: Black). However, while the testing procedure was fully functional, a problem discovered in the manufacturing process of the PCB boards hindered the detector construction. The lack of PCB passivation and the inappropriate PCB sanding contaminated the chamber's gas volume, rendering the detector inoperable. If the detector construction was put on a halt, a few prototypes with new or well-treated PCBs were made and qualified in order to study their performance and estimate their operability in the CMS experiment. As of 2025, a total of six (6) GE2/1 chambers are installed in CMS. Those new detectors are integrated within the unified GEM DAQ system and are operated similarly to their GE1/1 counterpart. On the brand new detectors, a very high efficiency can be reached, as measured on the prototypes during production, Fig 17 in the center, and confirmed after installation with the data of 2024, Fig 17 on the right.

Dr. Everaerts has also taken the lead on testing the final ME0 detector prototypes using cosmic rays and testbeams. In the CERN North Area the detector efficiency, spatial and time resolution were validated using muon beams. These studies were repeated in the CERN gamma-irradiation facility in the North Area to mimick the effects of the LHC's high-rate environment. In this facility the performance in the expected conditions could be verified. Since then, Dr. Everaerts also has taken the lead of the assembly lab at CERN. He has been developing the procedures and guiding the team on mounting the electronics on the ME0 detectors, performing the assembly into a final stack and the corresponding validations. During the electronics quality control, some problems occurred due to the new powering scheme. As a result, both the front-end electronics chips as well as the main electronics carrier board. Dr. Everaerts worked on finding solutions for these problems and is leading the implementation with the help of a students. Finally, Dr. Everaerts also leads the effort of the final performance of the 6-layer detectors in the lab using cosmic rays. In a few

months, Student Verace will join this effort.

5 Software and Computing

The UW group plays a strong role in development of software tools, based on machine learning and artificial intelligence techniques lately, as well as building and operating large-scale computing systems using distributed computing middleware developed by colleagues at UW-Madison. The UW group also operates one of the largest university-based computing facilities for HEP in the country under the supervision of Prof. Dasu. This facility was augmented with a large GPU cluster recently.

Our group has a key leadership role in U.S. CMS Software and Computing (S&C), with Prof. Bose serving as the U.S. CMS S&C Operations Program Manager. She oversees critical infrastructure including Tier-1, Tier-2, and Tier-3 computing facilities, networking, cybersecurity, software frameworks, data management, and computing operations. Prof. Bose is also actively driving R&D efforts to prepare for the HL-LHC era, focusing on adapting algorithms for heterogeneous computing, integrating AI/ML into operational workflows, and evolving computing architectures to meet future demands. Recent accomplishments under her leadership include the development of a strategic HL-LHC R&D roadmap [101], a modernization plan for computing facilities for Run 4 and beyond, and the launch of the "R&D Initiative" program—an annual opportunity that supports PI-driven HL-LHC computing projects aligned with U.S. CMS S&C program priorities. This initiative has fostered workforce development and broadened participation by bringing new individuals and institutes into S&C. Prof. Bose also serves as the CMS Heterogeneous Architectures Officer and is a member of the Offline & Computing Upgrade Office, where she is shaping the CMS strategy for heterogeneous computing and contributing to the O&C Conceptual Design Report.

5.1 HL-LHC R&D

Our group is actively involved in several HL-LHC R&D projects. As described in Sec. 3.5.1, postdoc Koraka together with graduate student Nelson (Advisor: Bose) has started to port part of the HLT electron reconstruction, the pixel matching algorithm, to run on GPUs. For offline, the CMS electron reconstruction takes up approximately 5% of the overall HL-LHC reconstruction time of which the pixel matching step dominates. The goal of our group's project is to finalize the porting and integration of the algorithm for Run 3 and then focus on potential optimization needed for the HL-LHC implementation.

Graduate student Elise Chavez (Advisor: Bose) has collaborated with Fermilab scientists on the Elastic Analysis Facility (EAF), a multi-experiment prototype designed to support scalable, low-latency analysis workflows using modern tools such as Jupyter, Kubernetes, and Dask. Chavez contributed to deploying EAF applications and CMS-specific analysis tools, co-authored a whitepaper for the European Strategy process [102], and continues to support benchmarking and scalability studies for upcoming Analysis Grand Challenges. Graduate student Martinez (Advisor: Black) will continue this work following Chavez's graduation.

Graduate Student Verace (Advisor: Black) is working with Fermilab scientists on developing a set of tools to benchmark and monitor network throughput for the HL-LHC networking needs. This will enable monitoring and testing of critical pathways to monitor the data transfers from CERN to Tier 1 and Tier 2 centers, as needed for the high data throughput of the HL-LHC.

MadGraph5_aMC@NLO is a widely-used event generator at the LHC, responsible for a substantial portion of our computing resource usage and projected to grow even further at the HL-LHC.

To meet growing computational demands, the MadGraph5_aMC@NLO for GPUs project is re-engineering the software to support Single Instruction Multiple Data (SIMD)-capable CPUs and GPUs, enabling efficient parallelization for event generation. As part of this collaborative effort, graduate student Thete (Advisor: Bose) has contributed to profiling and optimizing Madgraph GPU workflows using NVIDIA tools, and is currently implementing features to reduce computational overhead by consolidating similar physics objects within the source code and minimizing redundant Feynman diagram generation. The project has reached production-level support for leading-order processes and Thete's work was awarded the "Best Poster" award at the recently organized U.S. CMS Collaboration meeting. Together with Dr. Koraka, Thete is now exploring the integration of GPU-enabled event generation workflows within the CMS production system with future work targeting next-to-leading order support, phase space sampling, and speeding up of PDF evaluations in MG5_aMC@NLO.

5.2 GPU Integration for HL-LHC computing and ML workloads

Postdoc Dr. Koraka has led the commissioning and integration of our recently installed GPU cluster with the CMS central production system. In close coordination with the CMS O&C group, she enabled the successful submission of GPU-enabled workflows through the production infrastructure – an essential milestone for validating the physics performance of GPU algorithms across CMS. First presented at CHEP 2023 [103], this work lays the foundation for CMS's readiness to meet the computational demands of the HL-LHC. Looking ahead, our group is focused on integrating offline workflows with increasing fractions of GPU-accelerated code and ML inference tasks. These workflows will be tested first within the CMS production system and then deployed at High Performance Computing (HPC) centers, which are expected to play a vital role in augmenting CMS computing capacity during HL-LHC operations. Dr. Koraka is also leveraging our local GPU cluster to collaborate with others on CMS on exploring portable acceleration strategies, including coprocessors-as-a-service [104]. These efforts are particularly well-suited for ML workloads and are expected to yield substantial improvements in throughput and scalability. Dr. Koraka will play a key role in GPU-enabled reconstruction R&D effort and will work closely with Prof. Bose to help define the CMS strategy for heterogenous computing in the HL-LHC era.

5.3 SymbolNet: Neural Symbolic Regression with Adaptive Dynamic Pruning

Compact symbolic expressions have been shown to be more efficient than neural network models in terms of resource consumption and inference speed when implemented on custom hardware such as FPGAs, while maintaining comparable accuracy. These capabilities are highly valuable in environments with stringent computational resource constraints, such as high-energy physics experiments at the CERN Large Hadron Collider. However, finding compact expressions for high-dimensional datasets remains challenging due to the inherent limitations of genetic programming, the search algorithm of most symbolic regression methods. Contrary to genetic programming, the neural network approach to symbolic regression offers scalability to high-dimensional inputs and leverages gradient methods for faster equation searching. Common ways of constraining expression complexity often involve multistage pruning with finetuning, resulting in significant performance loss.

Recent Graduate Student Tsoi (Ph.D. 2024, CMS Thesis Award, Advisor: Dasu), working with MIT collaborators, built a tool called SymbolNet [105], which uses a neural network approach to symbolic regression specifically designed as a model compression technique, aimed at enabling low-latency inference for high-dimensional inputs on custom hardware such as FPGAs. This framework

allows dynamic pruning of model weights, input features, and mathematical operators in a single training process, where both training loss and expression complexity are optimized simultaneously. He introduced a sparsity regularization term for each pruning type, which can adaptively adjust its strength, leading to convergence at a target sparsity ratio. Unlike most existing symbolic regression methods that struggle with datasets containing more than O(10) inputs, Tsoi demonstrated the effectiveness of SymbolNet on three tasks with 16, 784 and 3072 inputs.

5.4 SymbolFit: Automatic Parametric Modeling with Symbolic Regression

Recent Graduate Student Tsoi (Ph.D. 2024, CMS Thesis Award, Advisor: Dasu), working with collaborators, built SymbolFit [106], a framework that automates parametric modeling by using symbolic regression to perform a machine-search for functions that fit the data while simultaneously providing uncertainty estimates in a single run. Traditionally, constructing a parametric model to accurately describe binned data has been a manual and iterative process, requiring an adequate functional form to be determined before the fit can be performed. The main challenge arises when the appropriate functional forms cannot be derived from first principles, especially when there is no underlying true closed-form function for the distribution. In this work, we develop a framework that automates and streamlines the process by utilizing symbolic regression, a machine learning technique that explores a vast space of candidate functions without requiring a predefined functional form because the functional form itself is treated as a trainable parameter, making the process far more efficient and effortless than traditional regression methods. We demonstrate the framework in high-energy physics experiments at the CERN Large Hadron Collider (LHC) using five real proton-proton collision datasets from new physics searches, including background modeling in resonance searches for high-mass dijet, trijet, paired-dijet, diphoton, and dimuon events. We show that our framework can flexibly and efficiently generate a wide range of candidate functions that fit a nontrivial distribution well using a simple fit configuration that varies only by random seed, and that the same fit configuration, which defines a vast function space, can also be applied to distributions of different shapes, whereas achieving a comparable result with traditional methods would have required extensive manual effort.

5.5 AI agent for Particle Physics Documentation

Recent graduate Mallampalli (Ph.D. 2025, Advisor Dasu) has developed an AI agent for querying internal particle physics collaboration documentation. With the increasing amount of publications (> 1000), supporting internal documentation (100s of pages for each publication), analysis discussion fora messages (100s of messages per publication), the maze of information available is overwhelming. New students and experienced analyzers often spend weeks getting useful and reliable information resulting in significant delays in obtaining physics results and increasing frustration during work. The work load of the physics analysis conveners and reviewers, who often are guiding multiple analyses at any time, is increased resulting in delays for the analysts. The core knowledge buried in this distributed set of documents needs to be made manageable and easily accessible. This task is especially suited well for large language models (LLMs). However, public LLMs such as ChatGPT do not have access to this privileged data. Mallampalli developed a Retrieval-Augmented Generation (RAG) based chatbot to help with this process. The goal is to get prompt and accurate answers to analysis related questions, backed up by the pointers to the sources.

Mallampalli's system populates a database having analyzed PDF documents (using optical character recognition), text pages, etc. Key words are converted to numeric vector labels and

interconnected using a distance measure in higher dimensional vector space, using machine learning algorithms. In order to preserve privacy of the collaboration the document access for embedding needed to create the vector database is done locally using manager privileges, and stored in a protected database. The response to user queries is generated by a local LLM. All of the system operates on the Wisconsin Tier-2, which houses several NVidia GPUs. Mallampalli plans to expand the chatbot's knowledge base by adding other privileged information from CMS, include abilities to understand graphic and tabular data. Perhaps, analysis code repositories could also be used in training to generate code from text based questions resulting in more efficient analysis processes. This work was presented at the Lepton-Photon 2025 symposium and was received well [107].

5.6 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 17506-jobslot computing cluster providing ∼200 KHS06 units of processing power and ∼13 PB (raw) high-availability distributed storage service. Recently, 19 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 di-boson 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, software development and computing operations and research. He supervises Dr. Savin, Dr. Sharma, and the graduate students Alharthy, Lomte, Mettner, Nee and Simeon, who are part of this proposal, and the project supported engineers and research software developers. Within CMS, Prof. Dasu serves as the deputy chair of the CMS collaboration board, while also representing the UW group. Beyond CMS, Prof. Dasu is playing a leading role in the muon collider design development, including supervision of some students in collaboration with accelerator physicists at FNAL. He currently represents the United States in the International Committee for Future Accelerators (ICFA).

Prof. Dasu works on SM measurements, Higgs sector studies, and dark matter searches. Prof. Dasu and his team focused on exploiting the τ-lepton trigger and reconstruction that they pioneered in CMS. Several students and postdocs trained by him have successful careers now. 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 good 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 high P_T mono-photon, mono-Z, mono-H and mono-Z' events. 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 Dr. Savin. Prof. Dasu ensures that his graduate students and postdocs are also engaged in good quality SM measurements. Following the Run-1 work on Wγ/Zγ (Gray Ph.D. 2012, now FNAL Staff) and ZZ (Ross Ph.D. 2013, now researcher in Computer Science at UW-Madison), WZ Taylor (PhD 2017), Run-2 work thus far has been on the ZZ kinematic distributions (Hussain Ph.D. 2021). Three graduate students Sreekala (Ph.D. 2022), Tsoi (Ph.D. 2024) and Mallampalli (Ph.D. 2025) graduated in the last 3-years, all of whom searched for new physics signatures. Of particular note is the recent machine learning and artificial intelligence work done with Tsoi and Mallampalli, discussed in this proposal. CICADA ML-based level-1 trigger implemented with Mallampalli, Tsoi, Savin and Sharma, with Princeton group, is a successfully deployed innovative new project. Prof. Dasu intends to continue his involvement in the Higgs measurements, extended Higgs sector searches and mono-object dark matter searches, with Savin, Sharma and his students.

Prof. Dasu leads 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, 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 beyond the HL-LHC. He is exploring potential of the 10-TeV/10-fb^{-1} muon collider energy-frontier machine, especially focusing on accelerator and its demonstrator development. He intends to promote the US P5 plans in international fora, in his role as the US Representative on the ICFA.

Prof. Dasu currrently serves as the Deputy Chair of the CMS Collaboration Board, which

has representatives from all CMS institutes. He is also serving on the muon collider collaboration leadership team.

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 Mason Austin and supervises Dr. Galloni. He leads the UW effort on the CMS CSC muon project, which includes his advisees, Dr. Galloni (50% CSC project) and, previously, Dr. Isabelle De Bruyn (at the Universite Libre de Bruxelles since 2024).

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, measurements of EFT parameters in multi-boson final states and searches for EW production of WZ and ZZ through vector boson scattering. Following the resent publications of analysis studying the differential production of ZZ and jets (JHEP with Mr. He, Dr. Savin) and EW 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 and measurements using the Run 3 13.6 TeV data. With Ms. Mondal and Dr. Savin he is studying Z boson polarization in ZZ production using the combined Run 2 and Run 3 datasets. This analysis should have the sensitivity to observe longitudinal vector boson production in inclusive ZZ production. With Marquez and Dr. Savin he is pursuing a first ZZ production cross section measurement in 13.6 TeV pp collisions. Also with Marquez he performing an indirect search for new physics using a full set of dimension 6 effective field theory SMEFT operators. This analysis will also leverage polarization to enhance the sensitivity to many of the EFT parameters. Prof. Herndon has performed many studies of the HL-LHC potential for studying EW production and led the SMP future physics group. The focus of his group on EW production and polarization is aimed at the goals of observing EWK ZZ production through vector boson scattering, measuring the SM QGC and the extraction of the longitudinal vector boson 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. Finally, he is co-chair of the SMP section of the CMS publication committee.

Under the onsite supervision of his former scientist, Dr. De Bruyn, Prof. Herndon's personnel participated in successful CSC phase 2 electronics upgrade, installation, and commissioning, and Run 3 data taking. Prof. Herndon is CSC resource manager coordinating personnel and in-kind resource contributions to the international CSC project. He is also USCMS L2 deputy end cap muon system (EMU) operations manager in charge of US personnel and funding for EMU operations. This position also involves planning and preparation for LS3 where all CSC and GEM chambers will be dismounted from the first end cap disks (YE1 disks) and then reinstalled and recommissioned, and the ME0 GEM detectors will be installed and commissioned. and the CSC and GEM backend electronics installed or upgraded. Planning for LS3 activities is at done at the granularity of days and maps out the activities and personnel necessary for the full four year period. Prof. Herndon manages projects such as the production of physical infrastructure and tooling including chamber extraction and mounting fixtures, chamber transporters and cooling services. Prof. Herndon's students and Dr. Galloni will be active during LS3 in onsite CSC activities involving dismounting, installation and commissioning. He is also the CSC representative on the muon conference and publications committee.

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. 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 characterization of efficiencies and the understanding of most sources of inefficiency. This upgraded code has been used for extensive studies throughout Run 3 to understand readout, HV, and instantaneous luminosity related sources of inefficiency and to provide feedback to the operations groups to successfully fix efficiency issues.

Prof. Herndon was the lead author of a recent review article covering standard model, top and Higgs cross section measurements published in physics reports [108]. Prof. Herndon is a co-convener of the LHC electroweak working group (EW WG) which has representative from the four experiments and theory community and studies precision EW physics, EW bosons and jets, and multi-boson production. Prof. Herndon also is a member of the permanent international organizing committee of the yearly Multi-boson Boson Interactions workshop. These activities that connect the experimental and theoretical physics communities have given him extensive contacts with those engaged in multi-boson physics and inform his physics research directions.

6.3 Professor Tulika Bose

Prof. Bose leads a comprehensive research program that integrates physics analysis, software and computing, and HLT development. She supervises Dr. Pinna and Dr. Koraka, and graduate students Parida, Chavez, Nelson, Thakore, and Roderick. Her physics portfolio spans precision measurements of Standard Model processes—such as $H \to \tau\tau$ and triple-top production—and a wide array of BSM searches, including dark matter, heavy di-Higgs resonances, and vector-like leptons. Her team has pioneered techniques for boosted topologies, including jet substructure-based triggers and deep learning-based tau tagging, while also contributing significantly to trigger operations, heterogeneous computing, and HL-LHC software and computing R&D.

Prof. Bose serves as an Advisor to the CMS Spokesperson and is a member of the CMS Management Board. She currently leads the U.S. CMS Software & Computing Operations Program, overseeing activities across 17 U.S. institutions. Her personal effort focuses on modernizing CMS software and computing infrastructure through the integration of heterogeneous resources (e.g., GPUs), including local clusters and national HPC centers. This work is critical for meeting HL-LHC computing demands and has led to her appointment as the CMS Heterogeneous Architectures Officer within the CMS O&C Upgrade Office.

Prof. Bose has held numerous leadership positions in the past, including CMS Physics Co-coordinator (PC) [2017 – 2019] and CMS B2G PAG L2 co-convener [2016 – 2017]. Under her 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 launch of CMS Physics Briefings and successfully engaged the collaboration in a long-term physics planning effort. She previously served as co-convener of the Electroweak Diboson and B2G Resonances sub-groups.

Her longstanding contributions to the CMS trigger system began in 2006, including development of HCAL trigger emulation and commissioning of the HLT. As convener of the Trigger Studies Group and later as Deputy Trigger Co-Coordinator (2011) and Trigger Co-Coordinator (2014–2016), she played a central role in the success of Run 1 and Run 2 HLT operations and the collection of high-quality datasets that have supported numerous CMS publications.

Prof. Bose has been recognized for her leadership in particle physics through her election as an APS Fellow for her contributions to the CMS physics program, trigger system development, and

BSM searches. She served as the topical group leader for the Snowmass Energy Frontier "EF09: BSM – More General Explorations," helping shape the national vision for BSM physics. She also co-convened the DOE Basic Research Needs (BRN) Study on HEP Detector R&D, where she led efforts on "Trigger and Data Acquisition (including Machine Learning)," identifying priority research directions and technological innovations needed across Energy, Cosmic, and Intensity frontiers. Most recently, she served on the Particle Physics Project Prioritization Panel (P5) and helped develop a long-term strategic plan for U.S. investments in particle physics.

Prof. Bose has a keen interest in outreach, science communication, and mentoring and workforce development. She has co-organized the U.S. CMS PURSUE internship program that provides research opportunities to undergraduate students from non-R1 institutions and serves on the Advisory Committee for Symmetry magazine. She is the lead PI for the TAC-HEP program that provides training in software & computing to graduate students and she serves as the project director of the Dept. of Education funded GAANN program that supports students from across the UW-Madison Physics department to conduct research while developing skills that will make them effective teachers and educators. Prof. Bose has a strong record of student/postdoc mentorship: recent graduates have gone on to postdoc positions - Loeliger (PhD 2022, now postdoc at Princeton University) and Shang (PhD 2024, now postdoc at TRIUMF lab) – while some others are now faculty members – Sperka (faculty at Boston University), Rankin (faculty at University of Pennsylvania), Carrera (faculty at National Polytechnic School, Ecuador).

Prof. Bose has a strong record of service to the community and was elected as the Secretary/Treasurer of the APS Division of Particles and Fields Executive Committee for 2022-2024 and is currently serving as Past Secretary/Treasurer. She has served on numerous other committees including the AURA Management Council for the Vera C. Rubin Observatory, the DPF Formation Task Force for Software & Computing, Fermilab Users' Executive Committee, and the US LHC Users Association Executive Committee. She serves as Associate Editor for the journal European Physical Journal C and regularly serves on many DOE/NSF review panels and committees.

6.4 Professor Kevin Black

Prof Black is engaged in physics analysis, several aspects of the GEM chamber upgrade (electronics integration, DAQ development, and operations), network upgrade R&D for the HL-LHC, and future collider R&D. 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 GEM-IB Chair, served 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. He supervises Dr. Everaerts who serves as the GEM system manager, and in the past served as both deputy GEM system manager and electronics integration coordinator. Prof. Black's group is currently working on the xDAQ software (Petre,Galloni, Teague), electronics noise protection (Galloni, Vetens, Teague), and GEM calibration and associated software (Galloni, Teague), and trigger primitive generation and timing optimization (Petre, Galloni).

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, Verace), and electroweak physics (Martinez). In addition, Black has

been the LPC co-coordinator from 2020-2024. 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. He served as main editor for the IMCC submission to the European Studies Group paper "The 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.

7 Activities of Key Personnel

CMS can not operate nor upgrade without the strong roles played by university scientists. Our senior scientist contributions are key to the success of GEM detector and level-1 trigger system upgrades. In recognition of their importance our scientists are appointed as managers of the projects they are leading, and are partially supported by the Operations program. As leaders they not only train our students and postdocs but also those of our collaborators. This section contains the profiles of our two lead scientists who we labeled as key personnel.

7.1 Dr. Pieter Everaerts

Dr. Everaerts currently serves as Project Manager for the CMS GEM muon project, overseeing all aspects of the project and coordinating with 35 institutes across 13 countries. Dr. Everaerts collaborates closely with Prof. Kevin Black. He leads the main production and quality control laboratory at CERN, supervising assembly operations and mentoring students. The team's current focus is the ME0 station, which aims to extend the coverage of the muon system up to $|\eta| = 2.8$. Dr. Everaerts has spearheaded multiple campaigns to verify that high levels of radiation and rates are sustained by ME0 under realistic conditions. Installation of this station is planned during LS3. During LS3 GE1/1 station will also be extracted to be refurbished, drawing on expertise

gained from operating the detectors and constructing new stations. Dr. Everaerts designed the refurbishment plan and will lead this effort.

Dr. Everaerts mentors students involved in the GEM project, most recently Aravind and Warden from UW. He brings extensive hardware experience, having played leading roles on several CMS subdetectors, including the silicon strip tracker, cathode strip chamber muon detectors, the high-granularity endcap calorimeter upgrade, and the GEM, with focus on project electronics testing, commissioning, operations, and system validation.

Dr. Everaerts has also contributed significantly to data analysis in BSM physics. He served as convener of the CMS SUSY group (L2) from 2019 to 2021, managing the entire SUSY search program. From 2014–2016, he convened the third-generation SUSY group (L3), leading the program targeting top and bottom squarks and staus.

He was a lead author on CMS's first W and Z cross section measurements and helped pioneer techniques for lepton identification as well as calibration and modeling of missing transverse momentum. He also co-authored the first CMS search for electroweak SUSY production and contributed to several follow-up publications. At the time, while strong SUSY production was becoming increasingly constrained, electroweak processes remained largely unexplored. As a result, the cross sections in the non-excluded regions of supersymmetry phase space had become comparable for strong and electroweak production. Dr. Everaerts developed CMS's first analysis targeting direct chargino and neutralino production in multilepton final states.

He initiated a complementary analysis focusing on multileptons with b-jets, aimed at detecting SUSY involving top and bottom squarks. This approach was designed to identify top squark production in scenarios where its signal mimics that of the Standard Model or where its cross section is too small. The analysis targeted cascade decays from gluinos or heavier top squark partners. Building upon this work, Dr. Everaerts led the CMS SUSY group's first comprehensive combination effort, unifying diverse analyses targeting similar SUSY scenarios. Initially developed independently for different final-state lepton multiplicities, these analyses had diverged in methodology over time. His leadership brought them together in a cohesive framework, culminating in a joint publication on third-generation SUSY production and providing key insights for future program development.

Dr. Everaerts played a central role in the single-lepton top squark search—optimizing selection strategies, improving dileptonic top background modeling, and devising novel, data-driven methods to estimate rare Standard Model backgrounds. Additionally, he led efforts to evaluate analysis sensitivity for the particularly difficult scenario in which the mass difference between the top squark and the lightest neutralino equals the top quark mass. This work yielded valuable guidance for CMS simulation strategies. Dr. Everaerts further developed an analysis targeting tau sleptons, including potential long-lived scenarios.

Over the next several years, Dr. Everaerts will continue to lead the GEM project through the completion of the ME0 station and GE1/1 refurbishment. This critical period demands strong leadership to ensure that the CMS muon system is fully prepared for the High-Luminosity LHC era. In parallel, he will continue mentoring students and driving forward innovative searches in BSM physics, focusing on possible long-lived particles.

7.2 Dr. Alexander(Sascha) Savin

Dr. Sascha Savin is a senior scientist with experience in trigger, software development and physics analysis. He has continuously held leadership positions in the collaboration and plays a supervisory role within and beyond the UW group. He works closely with Prof. Dasu and Prof. Herndon.

Dr. Savin is serving as the Co-convener of the Phase-2 L1 Calorimeter trigger group, which is part of the Phase 2 trigger upgrade project [90] that is aiming to completely rebuild trigger system

with FPGA-based cards. Together with UW engineers T. Gorski, A. Svetek and Princeton engineer L. Moreno the first multi-APx-cards demonstrator was built and is being used to check different design and algorithm proposals. The L1Calo trigger algorithm consisting of many blocks requires development of several firmware algorithms that will need to run on 34 APx cards. Dr. Savin led the group to build the first working prototypes of the Regional and Global calorimeter trigger, RCT and GCT, firmware (FW) and demonstrate its functionality.

Software emulating the trigger decision for use in MC studies and for validation of the hardware output is also Dr. Savin's responsibility. Together with Princeton PhD student S. Kwan, Dr. Savin developed the EGamma and RCT/GCT emulators that are under test. This work initiated and supervised by Dr. Savin is done by the UW, Princeton and Hyderabad students and postdocs.

Dr. Savin is also responsible for current operation of the L1 Calorimeter trigger. Together with UW engineer K. Das and UW PhD student H-F. Tsoi a 5BX readout to better control prefiring of L1 Trigger was implemented in trigger FW/SW and DQM. A new HCAL feature that allows the use longitudinal segmentation and timing of incoming particles was also implemented, to select Long Lived Particles in jets. Together with UW engineer A. Svetek, UW PhD students V. Shang and H-F. Tsoi Dr. Savin implemented these modifications for Run 3 operation. A new calibration strategy for Run 3 was also implemented by UW student A. Mallampalli under Dr. Savin's supervision.

From August 2019 till August 2022 Dr. Savin served as the Upgrade Performance Study Group (UPSG) co-convener. The UPSG was a group under Upgrade Coordination and Physics Coordination. It oversaw studies of physics cases relevant for the Phase 2 Technical Design Reports (TDRs) and provided input for any design optimizations. This included defining the physics benchmarks to evaluate the performance of the specific upgrade elements. With help of Offline & Computing, Physics Performance and Trigger Coordination groups it also overseen software developments with the goal to achieve a full Phase 2 reconstruction in the CMS software framework and ensure it proceeds in a timely fashion. The studies were performed in close contact with the Physics Object Groups (POGs) for what concerns objects and software, with the Physics Analysis Groups (PAGs) for the physics case and analysis. In 2021-2022 UPSG was responsible for organizing the CMS Snowmass activities. Under Dr. Savin supervision CMS completed 22 new analyses that together with 6 ATLAS new analyses and summary of the previous Yellow Report activities [109, 110], were published as joint ATLAS and CMS Snowmass contribution [111]. Dr. Savin was one of the main editor of the joint ATLAS and CMS White Paper publication CMS-FTR-22-001. He was invited also to contribute to a joint effort of a group of physicists and became a co-author of a "Future of the LHC" book that was published in Word Scientific in November 2023.

Dr. Savin personally contributed to an exceptionally large number of CMS physics analyses. Of particular note are the ZZ papers were published [32, 29, 112], including evidence of EWK ZZ production. The ZZ inclusive study was fully driven by UW PhD student U. Hussain. With UW PhD students S. Mondal and J Marquez, his goal is to measure different properties of the Higgs boson using its decay to ZZ to 4l, to investigate ZZ vector boson scattering and polarization processes, to analyze Run 3 data. The program also includes searches for high mass resonances and for anomalous gauge couplings. Dr. Savin started to work on ZH production with H decaying to bb and Z decaying to all possible channels with a group of UW students.

8 Activities of Junior Scientists and other PhD physicists

We have elected to promote our postdocs, who served the CMS experiment well in both operations and physics analysis for at least five years, as junior scientists. This section contains profiles outlining their strong contributions. The CMS experiment relies on them for smooth operations and

successful upgrades. As such, the U.S. CMS operations program funds them partially. Therefore, we are seeking remaining support for them to contribute to physics analyses. We anticipate that they will move on to permanent jobs in the field in the coming years, as the Covid remnants and the current financial crises fizzle out. When they move on, we will replace them with postdoctoral fellows. We note that four of our six former postdocs have moved on to faculty or staff scientist positions after training in our group. Furthermore, this section also contains profiles for UW teaching faculty and CMS researcher, Dr. Mohammadi, and postdoc, Dr. Koraka.

8.1 Dr. Camilla Galloni

Dr. Galloni works primarily on the CMS GEM Muon system working closely with Prof. Black. After joining the Muon GEM group in 2019, Galloni served as L3 Muon GEM coordinator of the DAQ software and firmware team from 2020 to 2022. She was responsible of the checkout and quality control activities of the GE1/1 detector right after its installation in 2020. From 2021, Galloni is the L2 Muon GEM Run Coordinator, in charge of the commissioning and operations of the GE1/1 and GE2/1 detectors during the Run 3 data taking. She provides on-site supervision of GEM students, from UW and elsewhere.

During the long shutdown (LS2), Dr. Galloni worked on the GEM DAQ software that was needed to readout and operate reliably the detector. The old C++ software had to be adapted, expanded, and integrated by Galloni with the xDAQ software used by CMS.

As L2 Muon GEM Run Coordinator, she fulfills the following important tasks. First of all the correct and reliable operation of the GEM detectors installed in the CMS apparatus. In case of a problem, this goal is achieved with a deep knowledge of the GEM system and managing a team of GEM experts on call, whose interventions can be summoned and orchestrated in case of need. During the years Galloni's developed a vast and long term experience on the GEM DAQ software, but also on the DCS (detector control system) that controls the detector HV, LV, and gas system, and all the related alarms and protection automatic actions.

She is responsible of the detector configuration, to ensure both the best achievable performance and operational reliability during the data taking. In order to do so she collaborated with students and other UW colleagues, Dr.Petre and student Warden, to develop an automatic procedure that measures promptly the GEM detector efficiency with the data of each run: a few our after the data is processed at the Tier0, plots to check the efficiency with high statistical accuracy are available.

Galloni served as CMS L3 Tau Identification group convener from 2017 to 2019. Under Galloni's coordination the DeepTau criteria were developed and became the baseline technique for the standard CMS taus identification for Run 2 and Run 3 CMS analyses[113].

In the future, Galloni is planning on continuing the work with the GEM detector , especially in view of the foreseen work of the long shutdown 3 (LS3: 2026- 2030). In this period, Galloni will provide guidance to the shifters involved in the refurbishment of the electronics of GE1/1 and the commissioning of the new GEM ME0 station. Both activities are being planned at the moment by Galloni and other GEM experts. During LS3, Galloni is going to work also on the CSC Muon detector, helping with extraction and refurbishment of the CSC ME1/1 chambers. From the data analysis point of view, Galloni will continue supervising students on searches and measurements for physics beyond the standard model.

8.2 Dr. Abdollah Mohammadi

This proposal seeks summer support for the UW teaching faculty member Dr. Abdollah Mohammadi to conduct CMS physics research with both graduate and undergraduate students. Over the

past three years, Dr. Mohammadi supervised eight undergraduate students and helped with the supervision of two graduate students.

He played a leading role in the first LHC measurement of boosted Higgs bosons in the $\tau\tau$ final state, resulting in publication in PLB [Phys. Lett. B 857 (2024) 138964]. This measurement extended the probed Higgs p_T region beyond 600 GeV, with observed (expected) significance of 3.5 (2.2) standard deviations. Furthermore, he contributed to the CMS combination paper for Higgs differential cross-section measurements, combining the boosted $\tau\tau$ results with other final states for unprecedented precision, providing information on the Higgs boson couplings.

Dr. Mohammadi contributed to the development of the Deep Boosted Tau reconstruction algorithm in CMS, and, together with UG student Elias Mettner, measuring its identification efficiency and data-to-MC scale factors for all three years of Run II. These are now used in multiple CMS analyses. Dr. Mohammadi is also beginning to use his machine learning based deep displaced tau reconstruction algorithm for searches of exotic Higgs decays to displaced 4τ final states. This is to conduct a search for LLPs from exotic decay of the Higgs boson in four displaced taus final state. These signatures are highly motivated in various model such as Fraternal Twin Higgs or Folded SUSY. To address the challenge of reconstructing displaced tracks due to long lived particles, he proposes to develop a machine learning based algorithm. This approach builds on the ParticleNet method used for jet tagging to incorporate features tailored for displaced tau reconstruction.

Dr. Mohammadi is also helping supervise graduate student Nelson on a search for new resonances decaying into a pair of Higgs bosons in the four tau lepton final state. This represents the first CMS search targeting heavy resonances in the mass range of 1-5 TeV, making use of the recently developed deep boosted tau algorithm pioneered by the Wisconsin group. Initial version of this analysis was carried out by undergraduate student Kristin Poppen from Gustavus Adolphus College under Dr. Mohammadi's supervision.

Dr. Mohammadi led the effort to set up and prepare the Fermilab Remote Operations Center (ROC) for central online trigger shifts, organized multiple L1 tutorial workshops, and trained several shifters at Fermilab. He also served as Level-1 Detector On Call (DOC) at CERN during the summers of 2023, 2024, and 2025. Additionally, he supervised undergraduates studying CICADA trigger performance on exotic signatures, demonstrating that CICADA can offer unique trigger capabilities where traditional triggers under-perform.

Dr. Mohammadi has also began a collaborative efforts for developing tau reconstruction algorithm for MAIA detector proposed for a future muon collider. The immediate goal is to evaluate the impact of the Beam Induced Background on the selection efficiency and mis-identification rate. This work is especially suited for working with undergraduate students.

8.3 Dr. Deborah Pinna

Dr. Pinna was recently promoted to the scientist track, after having completed five years of post-doctoral work, to continue to work closely with Prof. Bose and CMS students from UW and beyond. She is a two-time recipient of the LPC Distinguished Researcher award and has recently served as an L2 co-convener of the CMS Beyond-Two-Generations (B2G) physics analysis group. Since September 2023, she serves as the CMS convener of the LHC Dark Matter Working Group and helps define strategies and guidelines for dark matter searches across LHC experiments, coordinating with both experimental and theoretical communities. Her physics studies concentrate on searches for dark matter and other BSM phenomena and rare top quark production measurements. She has also been actively engaged in High-Level Trigger tasks and served as the co-convener of the STEAM group within the Trigger Studies Group. She has recently taken on a role within EMU operations and is engaged in trigger primitive development and optimization.

The CMS B2G physics analysis group is responsible for direct searches for new phenomena. During her convenorship, Dr. Pinna oversaw the integration of di-Higgs and exotic Higgs searches into the B2G program, and ensured timely delivery of results for Run 2 analyses. She reviewed all B2G results and publications and coordinated the preparation of more than 30 analyses to completion and publication. She organized workshops and tutorials to engage theorists and students in the development of new analysis strategies, ensuring a smooth transition to Run-3 physics.

Previously, as L2 STEAM convener, Dr. Pinna coordinated CMS trigger menu development and monitoring, critical for the Run-3 preparation. She performed HLT rate studies, including early GPU-based implementations, and mentored UW-Madison students in CPU-GPU performance comparisons. She engaged the broader physics community by organizing tutorials and lowered the barrier for physics groups to perform trigger studies. Building on this experience, she is now applying this expertise to GEM commissioning, optimizing readout, noise mitigation, and trigger primitive improvements toward HL-LHC.

Dr. Pinna has played a central role in CMS's dark matter search program, serving as MET+X L3 convener and overseeing the publication strategy and review of several CMS analyses. she was one of the leading contributors to the CMS analyses of dark matter produced with top quarks ($t\bar{t}$+DM at 8 [114] and 13 TeV [20, 55]) and later pioneered the first collider search for dark matter with a single top quark (t+DM) [24]. This novel analysis, motivated by her own phenomenological study [115], doubled the discovery potential for spin-0 mediator interactions compared to previous LHC results. This effort, is now published using the full Run-2 dataset [56], including new dilepton channels and improvements that yield a significant sensitivity gain beyond luminosity scaling. Dr. Pinna further extended her DM analysis portfolio by contributing to DM studies for future colliders. In particular, she led a search for DM using mono-photon events at muon colliders [85, 86] as part of the Snowmass 2021/2022 effort. For this work, Dr. Pinna mentored a UW undergraduate student who has since then graduated and joined Brown University as a graduate student.

Beyond dark matter, Dr. Pinna is actively engaged in several other analyses with UW students. This includes a first CMS analysis of triple top quark production, a sensitive probe of BSM physics and a first SM measurement as well as a search for narrow, high-mass resonances in the $HH \rightarrow b\bar{b}\tau^+\tau^-$ final state. These analyses utilize advanced reconstruction and ML methods to explore new phase space and significantly improve analysis sensitivity.

Dr. Pinna has a strong record of mentorship and training. She has guided students from UW-Madison and beyond in the development of analyses and has mentored students to perform GPU-accelerated HLT rate studies. She has organized CMS tutorials, exercises at the LPC, and fostered collaborations between theorists and experimentalists. She actively engages in outreach, including DM Days events at CERN, has contributed an invited chapter in "Advances in Cosmology" (2023), presented at the AAAS conference, and featured in The Economist podcast (2024).

8.4 Dr. Varun Sharma

Dr. Sharma was recently promoted to the scientist track after completing five years of postdoctoral work. He continues to work closely with Prof. Dasu, the CMS students from the UW and beyond. He serves as the CMS Trigger Technical Coordinator. Dr. Sharma has helped supervise several UW, Boston and Hyderabad students with CMS physics analyses in their searches for physics beyond the standard model. With these students, he published several physics analyses recently, looking for beyond the standard model signatures in monojet/W/Z[25], mono-photon [116], mono-Z' [52], mono-H($\tau\tau$) [53] and mono-H($b\bar{b}$) [54]. These searches for collider-produced dark matter play a complimentary role to direct detection experiments. Dr. Sharma also worked on searches for lepton flavor violating decays [46, 45] of the SM-like Higgs boson with the Notre Dame group.

Dr. Sharma, a CMS Achievement award winner, serves as the Level-1 Trigger Technical Co-Coordinator with major responsibilities to ensure smooth operations of all the Level-1 Trigger sub-systems. Working with L1 sub-system experts he plans and executes interventions for repairs, upgrades etc.. He maintains documentation of L1 trigger operating procedures, coordinate data quality monitoring and validation, communicate with high level trigger operations for the deployment of menus and prescales. Dr. Sharma is the first responder and CERN-based expert for the UW-built layer-1 calorimeter trigger. He has also been actively working on the development of physics algorithms and testing for the phase-2 upgrade of the CMS level-1 trigger system[90]. He was pivotal in implementation, commissioning and now operations of the novel CICADA machine learning level-1 trigger. Dr. Sharma has expertise not only in electronics systems operations but also in firmware development. He taught a course on high-level synthesis for firmware development on FPGAs to the TAC-HEP students twice.

Dr. Sharma served as a co-convener of Hadron/Photon Physics analysis sub-group. This group reviewed all physics analyses looking for new physics signatures with non-b-tagged jets and/or photons accompanied by missing transverse energy (MET), resulting in several Run-2 papers.

Dr. Sharma is now focused on measuring the SM Higgs decay to $b\bar{b}$ using all of Run-3 data, helping supervise the work of UW and Hyderabad students. Dr. Sharma plans to continue searches for dark matter signatures with Run-3 data with improved systematic uncertainties as well.

8.5 Dr. Charis Koraka

Dr. Koraka is a postdoctoral researcher in our group working closely with Prof. Tulika Bose. She holds leadership roles within CMS, serving as Level-3 (L3) co-convener of the Very Heavy Fermions (VHF) subgroup in the B2G physics analysis group and as L3 convener for GPU-based reconstruction within CMS Offline & Computing. In her role with the VHF subgroup, which focuses on searches for vector-like quarks and leptoquarks, Dr. Koraka oversaw the completion and review of over ten Run 2 analyses and helped launch multiple new Run 3 efforts, laying a strong foundation for the group's Run 3 physics program.

Dr. Koraka's own research centers on searches for vector-like leptons (VLLs), particularly in the two-lepton final state. In collaboration with graduate student Elise Chavez, she has introduced advanced machine learning techniques—including Deep Neural Networks (DNNs) and, for Run 3, Graph Neural Networks (GNNs)—to enhance signal-background separation and maximize sensitivity. She also leads a complementary analysis of top+dark matter signatures with graduate student Ameya Thete, leveraging CMS's novel anomaly detection techniques applied to scouting and parking data streams. This work aims to establish a model-independent framework for probing non-standard hadronic final states beyond the reach of traditional MET-based triggers.

Beyond physics analyses, Dr. Koraka plays a pivotal role in CMS's transition to GPU-accelerated computing. Together with graduate student Nelson, she is porting the electron pixel matching algorithm—one of the most computationally intensive components of CMS E/gamma reconstruction—to GPUs. As L3 convener in CMS O&C, she has led the integration of GPU-enabled workflows into CMS's central production system, enabling their use in release validation and physics performance studies. These workflows now serve as a benchmark for GPU algorithm validation across the experiment. Expanding this effort, Dr. Koraka and graduate student Ameya Thete are exploring GPU acceleration for event generation, building on recent developments in MadGraph GPU support to extend performance gains to earlier stages of the analysis pipeline. Dr. Koraka has also contributed to workforce development by designing and teaching a graduate-level training module on GPU programming with CUDA/Alpaka, equipping students with the skills to optimize algorithms for heterogeneous architectures and apply modern parallel computing techniques.

Name	Unit	Level	Position
Kevin Black	CMS	-	LPC Co-Coordinator (2021-24)
	CMS	Level-3	GEM Run Co-Coordinator (2020-22)
	CMS	Level-3	GEM Electronics Co-Coordinator (2022-24)
	CMS	Level-3	GEM Documentation Coordinator (2018-21)
	USATLAS	Level-3	Manager, L0MDT Upgrade (2016-18)
	USATLAS	Level-2	Manager, Physics Support (2016-18)
	ATLAS	Level-3	Co-Convener, Heavy Quark Exotics Group (2013-14)
	ATLAS	Level-3	Co-Coordinator, Muon Trigger (2012-16)
	ATLAS	Level-3	Co-Convener, Lepton+X Exotics Group (2006-10)
	ATLAS	Level-3	Coordinator, Muon Commissioning SW (2008-10)
Tulika Bose	USCMS	Level-1	Deputy S&C Operations Program Manager (2019-24)
	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 Group (2012-14)
	CMS	Level-1	Trigger Deputy Cordinator (2011-13)
	CMS	Level-3	Co-convener, EWK Diboson Group (2011)
	CMS	Level-2	Co-convener, Trigger Menu Integration Group (2007-11)
Sridhara Dasu	CMS	-	Co-Chair, CMS Career Committee (2019-23)
	USCMS	Elected	Chair, USCMS Collaboration Board (2014-16)
	CMS	Level-3	TriDAS Resource Manager (2012-14)
	CMS	Level-3	Co-convener, Higgs to Taus Group (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 Group (2012-13)
	CDF	Level-2	Co-convener, Higgs Discovery Group (2007-08)
	CDF	Level-2	Co-convener, B Physics Group (2006-07)
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)
Pieter Everaerts	CMS	Level-2	GEM Deputy System Manager (2022-24)
	CMS	Level 2	Co-convener, SUSY Physics Analysis Group (2019-21)
	CMS	Level 3	Co-convener, SUSY searches in 3rd Gen (2014-16)
A. Mohammadi	LHC	Level-2	Co-convener, WG3: BSM Higgs group (2022-24)
	CMS	Level-3	Co-convener, Higgs Exotic Decay Ggroup (2017-19)
	CMS	Level-3	Co-convener, Tau Identification Group (2014-16)
Deborah Pinna	CMS	Level-2	Co-convener, B2G Physics Analysis Group (2022-24)
	CMS	Level-3	Co-convener, MET+X Subgroup (2020-22)
Varun Sharma	CMS	Level-3	Co-convener, SUS Hadron/Photon Group (2022-24)
	CMS	Level-2	L1 Trigger Tech Co-Coordinator (2020-22)
	CMS	Level-3	Co-convener, EGamma Reco/HLT/Comm (2017-19)

Table 2: Past collaboration management positions held by the UW CMS group members.

References for CMS Task

The references to published papers and preliminary, but public, physics analyses are listed below, and cited in the narrative. They include only the work that Wisconsin group members have been directly responsible for. Wisconsin analysts produce HEPData entries and Rivet routines to document cross section measurements or limits and associated selections for appropriate publications. CMS conference database search shows that the group members have presented 43 talks at conferences since 2023, continuing the tradition of dissemination of scientific results. CERN Indico search shows that Wisconsin affiliated speakers made 16435 contributions to 2587 CMS events since 2002, indicating robust participation in the internal discussions. The references to talks are omitted.

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