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CMS at the LHC

1 Overview

The UW group of Profs Kevin Black, Tulika Bose, Sridhara Dasu and Matthew Herndon proposes to continue its active leadership role in the Compact Muon Solenoid (CMS) experiment [1] at the LHC, as we explore proton-proton collisions at 13 TeV and prepare for future higher luminosity running. The group is leading physics analyses in characterization of the Higgs Boson [2,3], searches for its potential partners, searches for particle dark matter, potential signatures of new physics in processes involving heavy quarks, top and bottom, and extensive studies of the electroweak processes. The UW group built, commissioned, operates, and upgrades major parts of CMS: the trigger system, including the Level-1 (L1) calorimeter trigger and higher level triggers (HLT), the endcap muon system (EMU), including its infrastructure, cathode strip chambers (CSCs) and the new Gas Electron Multiplier 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. Section 7 lists group management positions, current and past. Listings of papers written, conference presentations, and talks are in the references.

1.1 Transition Planning & Execution

Prof. Wesley H. Smith, who recently won the American Physical Society's prestigious Wolfgang Panofsky Award "*For the development of trigger systems for particle physics experiments, which measured the detailed partonic structure of the proton using the ZEUS experiment at HERA, leading up to the discovery of the Higgs boson and the completion of the Standard Model with the CMS experiment at the LHC*", was the leader of the group up until his early retirement last year. Prof. Smith worked with Profs. Dasu and Herndon in planning and executing the transition ensuring that the group is able to continue to meet the challenges of doing physics at the LHC, while supporting the proper upkeep and upgrade of the CMS detector. We were fortunate to recruit from Boston University, Prof. Black, who transitioned from ATLAS to CMS, and Prof. Bose, who was the Physics Coordinator of the CMS experiment. The UW has enthusiastically provided the necessary support for senior faculty hiring, noting our past successes in CMS and diligence in transition planning.

Because Profs. Smith and Dasu had jointly supervised Senior Scientist Savin, postdocs Caillol and Sharma, they were able to continue their work effectively through the transition as reported below. The trigger engineering team, supported by the M&O and Upgrade projects, is also able to continue to serve the CMS experiment without any hiccups. Addition of Prof. Bose, who also worked on CMS trigger systems at Boston helped mitigate the effects of transition for the trigger group at UW. Prof. Black, with his prior experience working on ATLAS muon systems, is able to strengthen UW CMS muon group joining Prof. Herndon and Senior Scientist Lanaro, to direct the work of Postdoc De Bruyn and their graduate students. Prof. Smith's younger graduate students have chosen to stay with the group and work under the supervision of Profs. Black, Bose and Dasu. Prof. Black and Bose were also able to attract new graduate students and postdocs Galloni and Pinna, who were supported by their startup funds, to enhance the group capabilities. The third Senior Scientist in the previous grant, Dr. Klabbers, has moved to a staff position with Fermilab.

1.2 Proposed Research Directions

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

The LHC operations are classified as Run-1 (2009-2012, 7-8 TeV cm energy, 36 fb-1) and Run-2 (2015-2018, 13 TeV cm energy, 160 fb-1). Having concluded the Run-1 analyses, with the thumping success of the discovery of the Higgs boson, and the initial Run-2 analyses, which firmly established the Higgs while not providing any evidence for new physics processes, the exploitation of the full Run-2 dataset remains in our focus. The complexity of physics signatures, backgrounds, detector conditions of full Run-2 data already mandates us to investigate multi-variate techniques using Machine Learning (ML) tools. The UW group proposes to deploy some ML techniques in its analyses as outlined below. The group is also beginning to work with colleagues in the Department of Computer Science and the Wisconsin Institute of Discovery on LHC-wide common efforts and in development of software and computing for successful execution of ML techniques, which are very resource intensive.

The impending Run-3 during 2021-2024, will operate at 13-14 TeV cm energy and is expected to double the available data, but under more stressful pileup conditions. One of the major challenges remaining is to continue to collect data of importance at the electro-weak scale under these adverse conditions. As the triggers using individual object reconstruction on FPGA-based technologies may lag in performance, we will investigate potential improvements using event-wide information in the spare capacities available in our FPGA trigger platform. We are proposing to investigate and prepare early applications for Run-3, noting the promise of High-Level Synthesis (HLS) of FPGA firmware to enable ML applications.

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 full Run-2 data and short-term Run-3 developments. Some of the work involves extensive simulations and usage of new computing resources with GPU and FPGA assisted environments.

The UW CMS group has a long tradition of providing its share of experiment support both in terms of maintenance and operation of the muon detector and the trigger systems. The group proposes to fully participate in acquiring the Run-3 data with personnel located on site at CERN. The group also maintains, operates and upgrades a productive Tier-2 computing center for CMS at Madison.

The UW CMS group also plays leading roles in the upgrades. The refurbished CSC chambers are being installed in Long-Shutdown-2, the GEM chambers are being built, the trigger electronics for HL-LHC are being produced. Senior group members play both management and supervisory roles. The detector qualification, calibration, software and firmware development tasks associated with these upgrades involve physicists supported on this task.

2 Physics Analysis Activity

2.1 Overview

Our primary physics activities are the study of electroweak symmetry breaking mechanism, searches for associated new physics phenomena, searches for the source of particle dark matter and other exotic phenomena. The 2012 discovery of the Higgs boson [2,3], in which our group played an important role, sets the context for our current and future research program. It strengthens the case for detailed study of the EWSB mechanism both by measuring the properties of the new boson and by investigating multiple-gauge-boson production. Our flagship analyses include leading contributions to the observation of Higgs coupling to fermions via τ-lepton pairs and also to the Higgs discovery decay mode into four leptons. Our electroweak physics analysis effort has resulted in papers on vector boson with heavy flavor production, di-boson production and searches for anomalous triple and quartic gauge boson couplings. Our searches and measurements in SM Higgs and vector boson physics have been leveraged into new physics searches in similar topologies.

We strive to maximize both physics output and variety. Prof. Herndon and Senior Scientist Savin focus on supervision of the SM measurements and associated new physics phenomena. Profs. Dasu and Bose, with Postdoc Caillol, focus on SM Higgs characterization. They also work with Postdocs Pinna and Sharma to search for new physics in both Higgs and dark matter sectors. Prof. Black is aided by Postdoc Galloni in the study of processes involving heavy-quarks, top and bottom, to look for signatures of new physics. Scientists Savin (trigger) and Lanaro with Postdoc De Bruyn (EMU), supervise student work on detector issues ensuring that high quality physics is enabled with smooth operations, and potential upgrades are thoroughly analyzed and realized during LHC shutdown periods. We require our graduate students to make a measurement in the context of the Standard Model and also search for new physics in similar final states, as well as receiving well-rounded training spanning vital experimental service roles.

UW group members routinely serve in the physics organization senior management. Detailed listing of positions they served in is listed in Section 7. They also participate actively in the collaboration reviews of analyses. Their constant involvement in physics efforts and diligent direction of student work resulted in the UW awarding 20 PhD degrees thus far. The group had the fortune of recruiting and mentoring 10 women PhD scientists, three of whom have faculty positions in HEP around the world.

2.2 Electroweak Physics

Measuring SM electroweak (EWK) processes is essential to understanding the gauge sector of the SM and further exploring the mechanism of electroweak symmetry breaking. Our group has continuously held leadership positions in the SMP group as indicated in Section 7 and is responsible for many important SM measurements at 13 TeV, and associated searches for new physics. Our contributions were crucial for CMS measurements of Z to ττ, W+jets, Z+jets, W+charm, W+b, γ+jets, Zγ, WZ and ZZ cross sections. Recently the UW group has focused on diboson physics and EWK production (Figure 1).

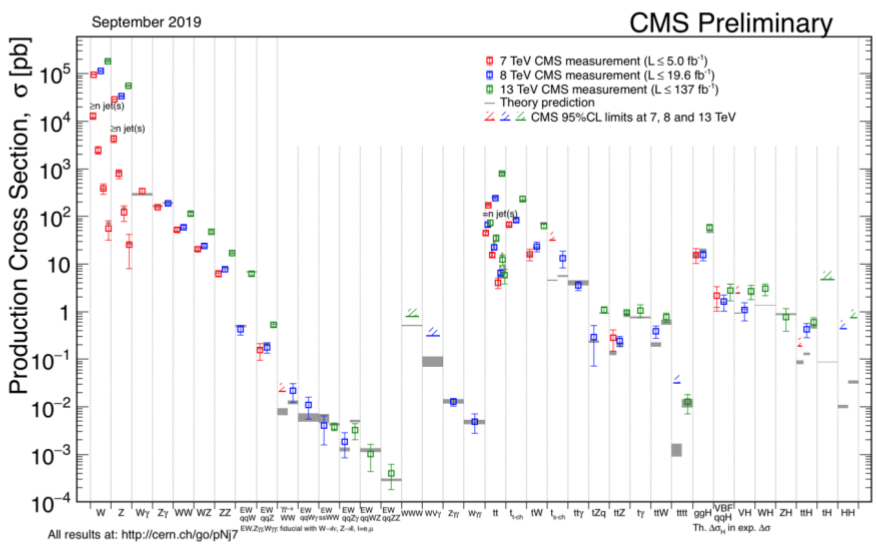


Figure 1: Measured production cross sections for various SM processes. Plot from Prof. M. Herndon.

2.2.1 Di-boson Physics

The UW group has a strong effort in analysis and leadership in the multi-boson subgroup of the Standard Model Physics (SMP) group. In 2012-13, Prof. Herndon and in 2016-17 Postdoc Duric (Advisor: Herndon) led the group. Starting in 2020 CERN Fellow and recently graduated UW student Kenneth Long (Ph.D. 2019, Advisor: Herndon) leads the group. UW analysis projects include QCD induced di-boson production and EWK production of both single and multiple heavy gauge bosons. The measurements encompass production cross sections, differential cross sections, anomalous triple gauge couplings of vector bosons (aTGCs), anomalous quartic gauge couplings (aQGCs), and the study of the pure EWK production mechanisms such as vector boson scattering and fusion. Many of these analyses have connections to both Exotica and Higgs physics searches for resonant decay to pairs of vector bosons as well as dark matter searches in vector boson production with missing energy topologies.

2.2.1.1 WZ production in SM and anomalous couplings

The UW group has previously measured cross sections and analyzed anomolous couplings at 7 and 8 TeV for WZ di-boson production. Graduate student Taylor (Ph.D. 2017, Advisor: Dasu) with Long, N.

Smith (Ph.D 2018, Advisor W. Smith), Woods (Ph.D 2017, Advisor: Smith), Postdoc Duric, and Senior Scientist Savin published the first measurement of the WZ cross section at 13 TeV[4]. Long was responsible for MC production and theoretical predictions, Smith performed background predictions while Woods and Taylor collaborated on the analysis framework with Taylor taking primary analysis responsibility.

Graduate student Long with Scientist Savin performed a search for EWK WZ production through vector boson scattering. This analysis also includes a sensitive search for anomalous quartic gauge couplings using effective field theory techniques and a direct search for charged Higgs production in via vector boson fusion [5]. Distributions used to extract the EWK WZ production cross section are shown in Figure 2, left. As part of the analysis, graduate student Long performed an extensive comparison of LO and NLO generators of EWK WZ signal and QCD WZ background production in collaboration with the authors of those programs. That study was the first of its kind and validated and determined the proper use of those generators [6,7]. Long's expertise in generators, QCD calculation and di-boson physics led to his appointment as SM MC group contact, CMS matrix element and generator group convener and after graduation appointment as a CERN Fellow and CMS SMP di-boson group convener.

2.2.1.2 ZZ production in SM

The UW group has previously measured cross sections and analysis couplings at 7 and 8 TeV for ZZ di-boson production. Graduate student Woods (Advisor: Smith) with Long, Dr. Duric and Dr. Savin have performed the first measurement of the ZZ cross section at 13 TeV [8], shown in Figure 2, right, as well as measurements of differential distributions involving jets[9]. Long contributed to the MC production and understanding of theory predictions, while Woods had the primary responsibility for the full analysis. Following this, graduate student Hussain (Advisor: Dasu) with graduate student Long and Dr. Savin have produced a preliminary cross section measurement using the full Run 2, 13 TeV dataset[10], Figure 2, and are working on an extensive publication [11]. The analysis was one of the first using the full Run 2 data set and achieved 3.7% uncertainty making it one of CMS's most sensitive cross section measurements. The full publication will include differential distributions with comparisons to NNLO QCD calculations from MATRIX and anomalous coupling constraints. This type of measurements should be performed in all production and decay modes and with undergraduate Downham, Prof. Herndon is studying the statistical sensitivity of each of the QCD induced and EWK di-boson production and decay modes to understand the best prospects for further studies.

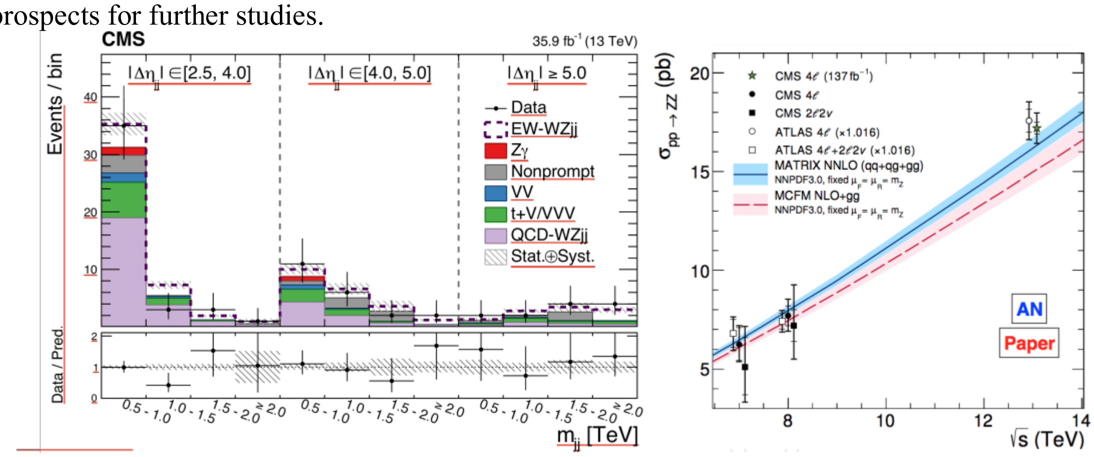


Figure 2: Distributions of EWK WZ events (left, Long) and measurement of ZZ cross sections as a function of pp center of mass energy (right, Hussain).

2.2.1.3 W & Z boson production and rare W decays

Former Postdoc Duric was an author on the 13 TeV Run 2 publications of the EWK produciton of single W[12] and Z [13] bosons with two jets. Her contribution focused on searches for aTGCs. Of particular interest is that the aTGC signals are simulated using effective field theory operator techniques which makes it possible to simultaniously consider the contribution of operators to both gauge boson and

Higgs boson physics (VH Higgs analysis). The results of these analysis were combined using a framework Dr. Duric developed for anomalous coupling limits.

Postdoc Caillol (Advisor: Dasu) has studied the rare decay of the W boson to three pions [14]. This analysis achieves the most stringent limit on an exclusive decay of the W boson and was the first publication of a search for this rare decay.

2.2.1.4 Zγ Analysis

Following on previous measurements of the Zγ cross section and anomalous couplings at 8 TeV Graduate students Buchanan (Ph.D. 2019, Advisor: Dasu), Perry (Ph.D. 2016, Advisor: Smith) and Postdoc Gomber (Advisors: Dasu and Smith) performed preliminary cross section measurements at 13 TeV in the Zγ → ννγ channel [15]. This analysis exploited the higher statistics of the neutrino decay mode of the Z boson. The complete 13 TeV analysis in progress includes a differential measurement of the photon cross section with unprecedented sensitivity to the photon transverse momentum spectrum and aTGCs at high energy [16]. The results are compared to NNLO predictions from MATRIX (Figure 3). This work is leveraged to produce dark matter searches in the same topology (see below).

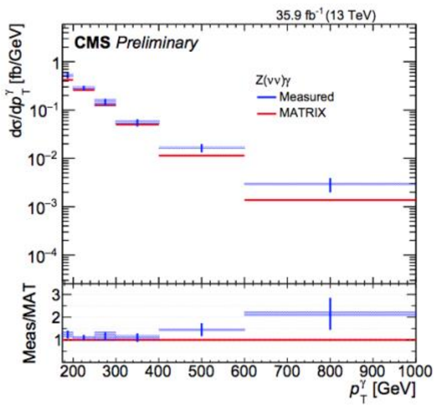


Figure 3: Transverse momentum of the photon in Zγ production. Buchanan

2.2.2 Proposed research: QCD and EWK Di-boson production and polarization.

Graduate student Long (Advisor: Herndon) performed the first analysis of EWK WZ production at CMS. Building on this work graduate student Teague (Advisor: Black) with Prof. Herndon and Dr. Savin have studied the potential of the full HL-LHC dataset to measure EWK WZ production and study polarization [17]. Polarization can be used to extract longitudinal vector boson scattering via the Higgs, which allows further study of the mechanism of electroweak symmetry breaking. Using the full 13 TeV Run 2 data set graduate students Stephen Trembath-Reichert and He He (Advisor: Herndon) will study EWK production and polarization in both QCD and EWK production of the individual vector bosons as a function of energy in the WZ and ZZ final states respectively. In both cases, they intend to use state of the art deep learning techniques to improve signal extraction. New MCs that allow tracking of polarization information and NLO generation will be essential to these studies. These types of studies are a prerequisite to the study of longitudinal vector boson scattering. In addition, polarization information has sensitivity to anomalous couplings including the ability to separate the contributions of different operators.

2.3 Higgs Physics

2.3.1 Higgs Decays to Z pairs in lepton modes

Graduate student Hussain (Advisor: Dasu) and Scientist Savin are primary Wisconsin contributors to the analysis of Higgs decays to Z-pairs in the four-lepton mode. These analyses have resulted in several papers [18], and have firmly established 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), Woods (Ph.D. 2017, Advisor Smith) and Scientist Savin, played an important role in the discovery of the lighter 125 GeV Higgs boson [2,3] and subsequent initial characterization of the H(125) using Run-1 data.

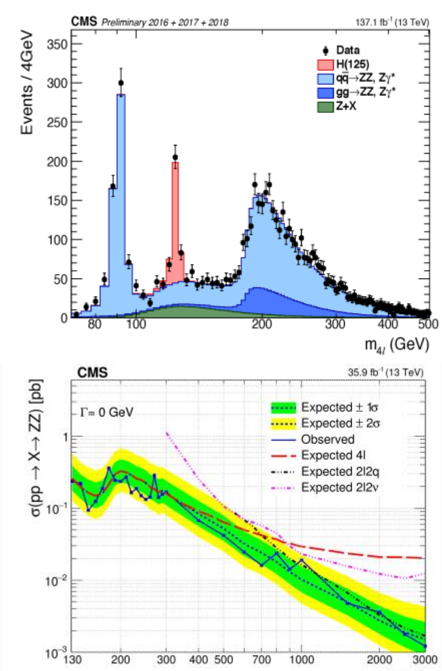


Figure 4 Four lepton invariant mass showing Z, H and ZZ (top); Exclusion of additional Higgs bosons.

They had also explored the high mass region extending limits on production of additional scalar resonances with masses up to 3 TeV, with various widths [19] Figure 4. This work involved collaboration with Florida, JHU and many European groups.

SM Higgs Decays to tau pairs

The SM decay $H \rightarrow \tau\tau$ 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), former postdocs Friis and Ojalvo (Advisors: Dasu & Smith) and Scientist Savin made extensive contributions [21-22] to CMS searches for Higgs boson decays to tau pairs, using $e\tau_h$ and $\mu\tau_h$ modes with boosted and Vector Boson Fusion (VBF) categories using Run-1 data. CMS success in this effort was due to comprehensive work ranging from triggers and reconstruction as evidenced by sustained leadership of the Tau Physics Object Group (Past Conveners: Savin, Friis & Ojalvo (UW)) and the H2Taus Physics Analysis Group (Past Convener: Dasu & Current: Caillol). Bachtis' thesis won the CMS 2012 best thesis award. Caillol won the CMS 2017 best thesis award as well. The Run-2 (2016-only) analysis led by 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 of the Higgs boson at M_H=125 GeV upon including Run-1 data [22]. The signal-weighted di-τ mass distribution of most sensitive and combination of all channels and categories are shown in Figure 5, with an inset of the background-subtracted spectrum. Graduate student Loeliger (Advisor: Bose), Sreekala (Advisor: Dasu) and Postdoc Caillol are collaborating with colleagues from Princeton, KSU and JHU to finalize the full Run-2 result in Spring 2020 [23]. Having pioneered τ-reconstruction and performance [24], the addition of VH production modes [25] and extraction of the fermion and vector boson Higgs couplings [25] in the past, we intend to update those analysis to full Run-2 dataset as well by Spring 2021.

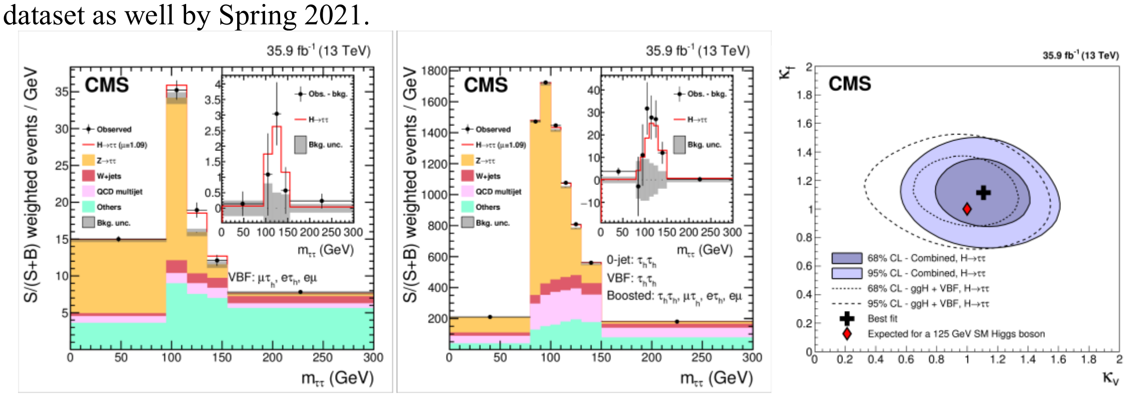


Figure 5: Most sensitive VBF-tagged τ-pair mass distribution (left), combined distribution for all channels and all categories (center). Including W & Z associated production [25], the extracted fermion vs vector boson higgs coupling strengths including VH production modes (right) [2625].

2.3.2 Proposed research: SM Higgs Physics

Profs. Bose and Dasu, Senior Scientist Savin, Postdoc Caillol, and Graduate students Loeliger (Advisor: Bose), and Sreekala (Advisor: Dasu) will continue their strong role in Higgs physics, especially the analyses involving taus. The goal is to measure the differential distributions of production cross sections to compare with N3LO calculations, which are becoming available, and also improve coupling measurements to fermions and bosons, using the VH production process and τ-pair decays later in 2020.

Improvements in the measurement of H(125) coupling to fermions and the observation of di-higgs production in the τ-pair and b-pair modes in Run-3 to HL-LHC period, mandates trigger and reconstruction developments championed by the UW group. We propose to continue work in this vein on both trigger and analysis fronts using ML techniques.

2.3.3 MSSM Higgs Decays to tau pairs

For certain regions of parameter space, MSSM Higgs bosons decay preferentially to tau pairs. The UW group put special emphasis on tau identification and reconstruction from the outset, turning out the World's best limits in the field even with 36 pb^{-1} data from 2010. The UW team of Bachtis (Ph.D. 2012, Advisor: Dasu), Ojalvo (Ph.D. 2015, Advisor: Smith), Dodd (Ph.D. 2018, Advisor: Smith) and Ruggles (Ph.D. 2018, Advisor: Dasu), Senior Scientist Savin and postdocs Friis, Ojalvo and Caillol continued these searches using both Run-1 and Run-2 data over the past years (Figure 6) [27].

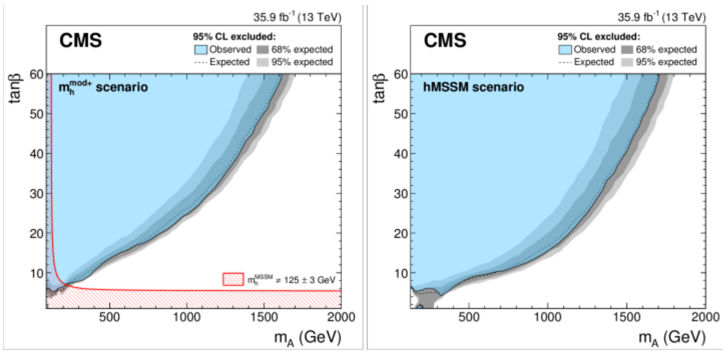
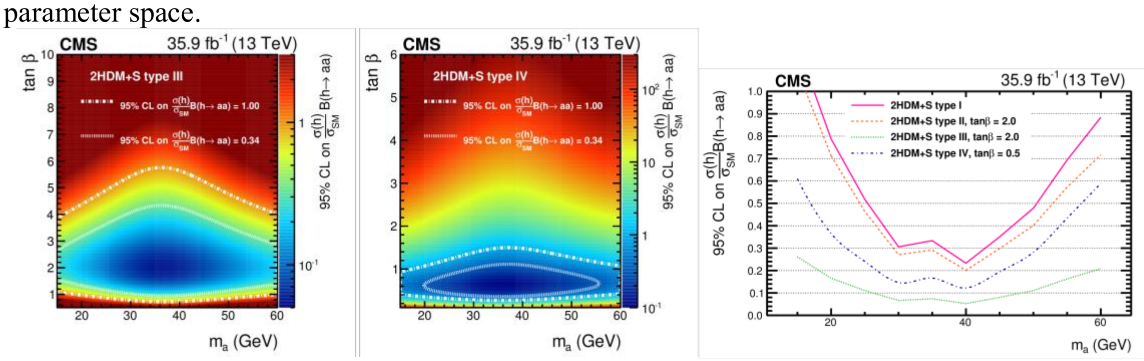


Figure 6: The 95% excluded regions of the MSSM parameter space for two scenarios of other SUSY parameters and low tanb region constrained by our ZA-search in one such scenario.

For low tanβ and $m_A < 2m_{top}$, the heavy scalar MSSM Higgs boson H decays preferentially to a light h(125)-pair, in turn decaying to a b-pair or τ-pair. Dodd and Ojalvo searched for such heavy Higgs decays using Run-2 data in 2τ+2b state. Similarly, the pseudoscalar MSSM Higgs boson A decays to a Z boson and a light Higgs boson, h(125). Ruggles and Calliol searched for A-boson in 2l2τ mode. All these results were negative, yielding an exclusion region in m_A-tanβ plane (Figure 6, right) [28]. The UW group plans to continue all three of these MSSM searches, as it will take several hundred fb^{-1} to fully explore the parameter space.



Figure

Figure 7: 95% CL limits on cross section times branching fraction of SM H, scaled to SM H cross section, for several 2HDM+S scenarios as a function of pseudo-scalar a-boson mass and relevant parameters.

2.3.4 Light Pseudo-scalar Higgs

The next-to-minimal super symmetric standard model (nMSSM) and generic models with two higgs doublets and a scalar (2HDM+S) contain a light pseudo-scalar Higgs boson called the a-boson, which decays to a fermion pair. These models have attractive theoretical features eliciting our interest. The a-boson is often produced in h(125) decays with significant branching fraction. Postdoc Caillol had completed a search for this a-boson in the modes h→aa, followed by a→μμ, a→ττ and a→ bb, depending on the mass of the a-boson. Initial results shown in Figure 7 using Run-2 data are published [29]. Analysis of full Run-2 data is beginning with new summer graduate student Tsoi (Advisor: Dasu) and Postdoc Caillol. This analysis involving low p_T final-state τ-leptons, presents an analysis challenge, possibly helped by ML techniques. Although the analysis has low background at analysis level, triggering presents a major challenge requiring multi-object event-level correlations. We propose to investigate possible use of ML techniques at trigger level for Run-3.

2.3.5 Lepton Flavor Violating Higgs Decays

Lepton flavor conservation in the Standard Model is accidental. Charged lepton flavor violation in their Yukawa couplings to Higgs can be directly tested at the LHC. Graduate student Levine (Ph.D. 2016, Advisor: Dasu) and former postdoc Cepeda observed a small excess (2σ) in lepton flavor violating Higgs boson decay to a muon and a tau using Run-1 data [30,31], resulting in much speculation by the theory community. A quick follow up using 2015 data indicated that it is most probably a statistical fluctuation [32]. Postdoc Calliol, in collaboration with Notre Dame and CERN groups, completed the much-anticipated 2016 resolution of this issue, which produced a result (Figure 8) consistent with no excess [33].

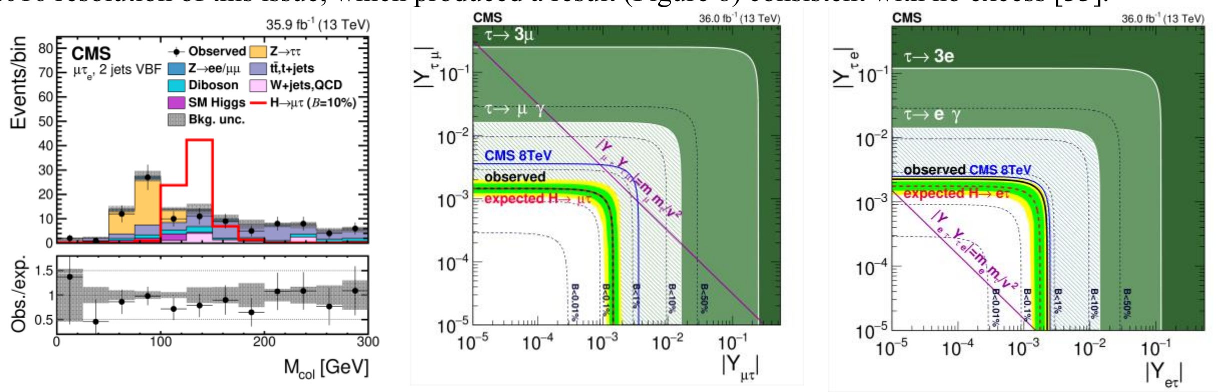


Figure 8: Collinear mass spectrum of muon and tau system (left), 95% CL limits, from H to μτ (center), and eτ (right) searches, obtained on Yukawa couplings, showing that results are consistent with SM.

2.3.6 Invisible Higgs Decays

There is a large range of parameter space in several new physics models, e.g., MSSM, where there exists a H(125) that can decay invisibly. Current accuracy of the LHC datasets allow significant room, amounting to a 35% branching ratio of H(125) to invisible states. A search for such decays is also motivated by the possibility of a discovery of a dark matter particle candidate through this Higgs portal. Graduate student N. Smith (Advisor: W.H.Smith) and former postdoc Gomber (Advisors: Dasu & Smith) have searched for invisible Higgs decays using ZH associated production mode, where the Z-boson decays to light leptons [34]. No signal has been observed, as shown in Figure 9, resulting in our setting an upper limit on the production times branching fraction of H(125), which is produced in association with a Z-boson and subsequently decays invisibly. In combination with the VBF-tagged and ggH tagged analyses, we limit the invisible branching fraction of H(125) to below 20%. Analysis of complete 2016 data is already underway in collaboration with the MIT and Northeastern groups [35].

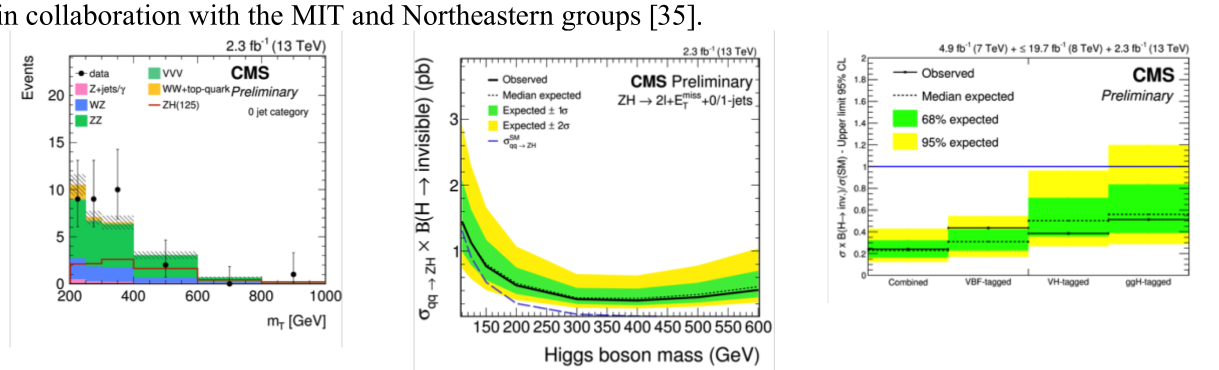


Figure 9: Transverse mass of Z(ll)+MET selection using 2015 dataset (left), limit on invisible-H cross section times branching fraction (center) and the combination all modes and all data through 2015.

2.3.7 Searches for new physics in DiHiggs production

Postdoc Galloni (Advisor: Black) is the author of several boosted diboson searches looking for narrow mass resonances. She was a primary author of searches for a high mass-resonance decaying into ZH, WH and HH boson pairs [36-37]. While SM diHiggs production is a direct measurement of the Higgs self-coupling and critical to understanding the shape of the Higgs Boson potential, the cross-sections are so small that it is expected that it will not be observable until the full HL-LHC dataset is analyzed. However, several viable BSM models predict heavy resonances decaying into pairs of Higgs Boson pairs. Examples include Kaluza-Klein (KK) excitations of spin-0 radions (Figure 10) or spin-2 gravitons. Dr Galloni developed an algorithm to identify boosted b-pairs [38] which was finalized and published shortly after joining UW.

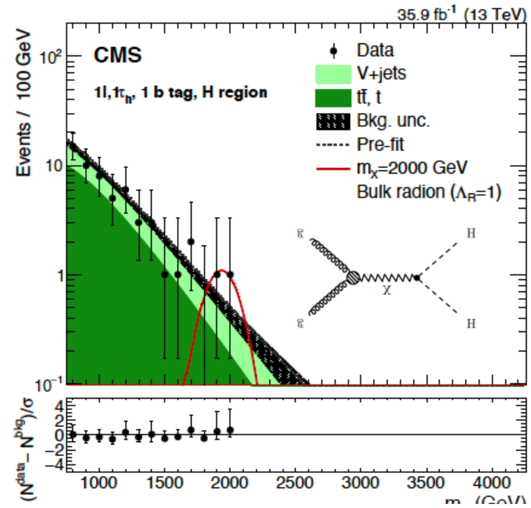


Figure 10: DiHiggs invariant mass distribution.

Proposed Research: Dihiggs Resonances

Dr. Galloni (Advisor: Black) and graduate student Abigail Warden (Advisor: Black) will work on extending the diHiggs analysis to use the full data set and to search for both resonant and non-resonant pairs of Higgs bosons both as a search for new physics and in preparation of the Standard Model analysis. Warden will analyze the ττbb final state allowing her to leverage the extensive group knowledge of τ reconstruction and triggering at UW along with using a ML algorithm that will optimize the search.

2.3.8 Proposed Research: BSM Higgs Physics

If the MSSM is realized in nature, the Run-1 and early Run-2 results are indicating that the lightest of the neutral bosons is very much SM-like and is identified as h(125). The heavier neutral MSSM Higgs bosons H and A decay predominantly to the third generation for large tanβ, and are best observed in τ-pair mode. While our current results provide the best exploration to date, much parameter space is left unexplored. We intend to continue this exploration using increased statistics of full Run-2 data and prepare with sophisticated triggers and analyses for Run-3 and beyond.

If the nMSSM is realized in nature, an additional light pseudo-scalar Higgs boson exists, and is best discovered in the decay h(125)→aa. Depending on the mass, the pseudo-scalar Higgs decays to τ-pair are important as shown by our work earlier. UW will continue to search for this pseudo-scalar.

In extended Higgs sectors, doubly charged bosons occur. These extensions of the Higgs sector are interesting due to their neutrino mass connection. The doubly charged higgs boson decays are spectacular, yielding like-charge lepton pairs with very low backgrounds. The early Run-2 analysis is in the final stages of approval, but much of the parameter space will remain uncovered. We will look for an unambiguous discovery even with a few events peaking up in this low background channel, as we continue to explore the high mass end using Run-2 data and beyond.

Lepton-flavor violation in Higgs decays remains a possibility, although the initial indications from Run-2 have all but squashed the observation of a 2-σ excess in the search for H→μτ decays from Run-1. This parameter space can be covered more thoroughly as we accumulate statistics; as such a measurement is not yet systematically limited. The full Run-2 analysis will begin as soon as the full Run-2 SM H to τ-pairs analysis is complete.

ML techniques, which we propose to develop with broad collaborations, are especially important for BSM Higgs exploration, both for low mass particles, due to large backgrounds, and high mass ones, due to merged final-state objects.

2.4 Dark Matter Search

Weakly interacting massive particles are among the most favored candidates for explaining the overwhelming evidence for dark matter in our universe, which is established using its gravitational interactions. If the dark matter (DM) is made of particles, which are light enough and interact with sufficient strength with normal matter, the LHC should be able to produce them in proton-proton interactions. However, the dark matter particles will escape the CMS detector leaving no trace. Nevertheless, one can search for such dark matter particles produced in reactions with initial state radiation that recoils from the dark matter candidate. Portals to dark matter comprising the newly discovered Higgs boson or hitherto unknown force particles are also possible. Models of interactions mediated by a new scalar and/or pseudoscalar have become popular recently – they are theoretically well-motivated and can be easily accommodated in extended Higgs sectors. Our group has been actively analyzing the Run 2 data covering the above research directions and this work has already resulted in several publications based on the 2015/2016 dataset. Analyses are currently ongoing using the full Run 2 dataset.

Our group has a leadership role in this area with postdoc Pinna (Advisor: Bose) acting as the co-convener of the "MET+X" sub-group within the EXO physics analysis group together with former postdoc B. Gomber (now an Assistant Professor at the University of Hyderabad, India). As leader of the MET+X sub-group, Pinna is responsible for overseeing all of the CMS dark matter searches.

2.4.1 Mono-γ Analysis

Graduate student Buchanan (Advisor: Dasu) and former postdoc Gomber (Advisors: Dasu and Smith) had searched for mono-γ signature in both 2015 [39] and early 2016 [40] data. As proposed in our previous grant proposal, the analysis strategy was improved upon and a paper was published in 2018 with the full 2016 dataset. Figure 11 from the paper [41] shows that the photon and missing transverse energy spectra are consistent with SM production rates resulting in limits in the context of simplified models, which are also converted, with certain assumptions for mediator mass and spin-parity, to dark matter nucleon interaction cross section limits to compare with direct dark matter search experiments. The results are also interpreted in the context of models with extra dimensions resulting in a 95% CL lower limit on the modified Planck scale, M_D.

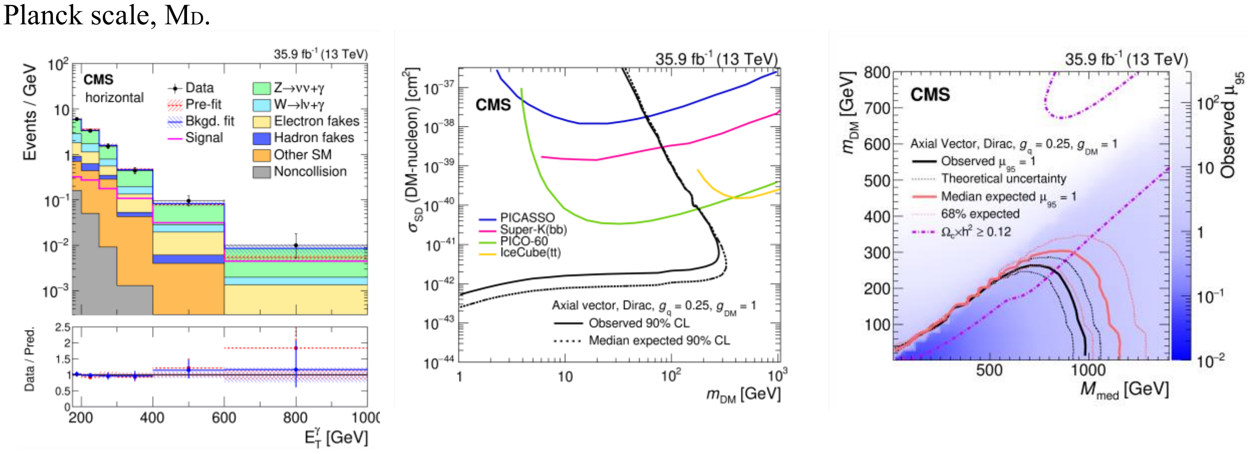


Figure 11: The missing E_T spectrum (left) for mono-photon event selection, 90% CL limits on dark matter-nucleon interaction cross section for axial vector (center) couplings in comparison to direct search experiments and exclusion region in mediator versus dark matter mass space (right) are shown.

2.4.2 Mono-H Analysis

Former graduate student Dodd (Advisor: Smith) and former postdoc Gomber (Advisors: Dasu and Smith) used our group's expertise in the study of SM Higgs boson decays to τ-pairs, to search for such a H(ττ) candidate recoiling from large missing transverse energy [42]. The connection of the Higgs boson with dark matter is an especially important case to study. In Higgs portal models, an additional Z' boson exists and decays primarily to the SM-like Higgs boson (h of 125 GeV) and a heavy Higgs boson (e.g., the heavy pseudo-scalar A in 2HDM). The A in turn decays primarily to a pair of weakly interacting massive particles, which are dark matter candidates. The analysis was the first search for dark matter produced in association with a Higgs boson decaying to two τ leptons (Figure 12) and the results were combined with the $\gamma\gamma$ channel to produce upper limits on dark matter production [43]. The analysis is currently being updated to use the full Run 2 dataset by graduate student Jithin Sreekala (Advisor: Dasu).

2.4.3 Mono-Z' Analysis

Graduate student Hussain (Advisor: Dasu) and postdoc Sharma (Advisor: Dasu) are searching for a dark matter candidate interacting with the standard model fermions through a very weakly coupling light vector boson (Z'). In this model, pioneered by Prof. Yang Bai (UW) and collaborators, a thin pencil-like jet recoiling from a large missing transverse energy is produced. The pencil jet finder and analysis framework has been set up and the event selection optimized. The analysis of the full Run 2 dataset is in progress and preliminary results are quite promising as shown in Figure 12.

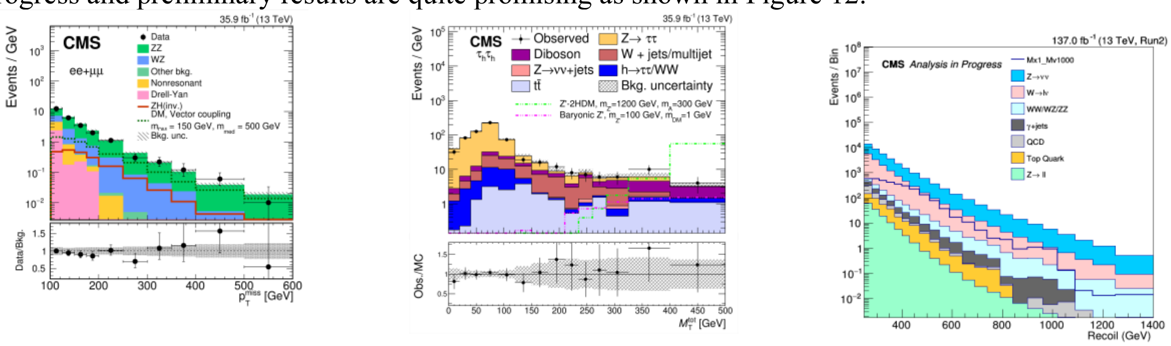


Figure 12: Signal region spectra of E_{Tmiss} for mono-Z selection (left) and transverse mass distribution of τ-pair + MET for mono-H selection (center) indicating good agreement with SM background predictions. The recoil distribution for the mono-Z' pencil-thin jet selection (right) (data is still blinded).

2.4.4 Mono-Z Analysis

Former graduate student N. Smith (Advisor: W.H. Smith) and former postdoc Gomber (Advisors: Dasu and Smith) searched for a Z-boson, reconstructed using its e^+-e^- and μ^+-μ^- decays, recoiling from the missing momentum using both 2015 [44] and early 2016 [45] data. The analysis was updated with the full 2016 dataset and the results published [46]. The results are consistent with the expected background from the Standard Model processes, dominated by the Z(*ll*)Z(νν) process at high missing E_T(Figure 12). This result enabled placing exclusion limits on simplified dark matter models, and is interpreted as a 95% CL upper limit on the dark matter–nucleon interaction cross section, for vector and axial-vector coupling. The results are also interpreted within a scenario with a standard-model-like Higgs boson produced in association with the Z boson and decaying invisibly, a model of unparticle production, and a model with large extra spatial dimensions.

2.4.5 Top + Dark Matter Analyses:

While the landscape of viable DM interactions with SM particles is large, the possibility of interactions mediated by a new scalar and/or pseudoscalar is theoretically attractive in extended Higgs sectors. Assuming minimal flavor violation, the couplings between the neutral spin-0 mediator and the SM particles are proportional to the fermion masses motivating searches for DM in association with top.

$t\bar{t}$+DM analysis: Postdoc D. Pinna (Advisor: Bose) has been one of the major contributors to the CMS $t\bar{t}$+DM analyses performed with the data collected at 13 TeV in 2015 [47] and 2016 [48]. The latter analysis (Figure 13) provided the best sensitivity for the scalar mediator model and had better sensitivity for spin-0 mediators than dark matter production in association with a jet (previously considered to be the most sensitive signature).

t+DM analysis: Recently, Pinna extended the $t\bar{t}$+DM search to a single top quark (t+DM), which had never been performed before at colliders [49]. $t\bar{t}$+DM processes were analyzed together with the additional t+DM production mode relying on both the semileptonic and hadronic decay channels of the top quark. To enhance the sensitivity of the search to t+DM events, Pinna exploited new discriminating variables based on signal topology for dedicated event categorization. On analyzing the full 2016 dataset, no significant deviations with respect to SM predictions were observed in the data, as shown in Figure 13 (center). Upper bounds at 95% CL were set on the ratio between the measured and theoretical cross sections assuming a new scalar or pseudoscalar mediator particle, and the results are shown in Figure 13 (right) for the scalar case. This first limit on t+DM led to upto a factor of two improvement at high mediator masses on the limits when compared to previous results. Pinna and graduate student Victor Shang (Advisor: Bose) are currently working on updating the t+DM analysis with the full Run 2 dataset.

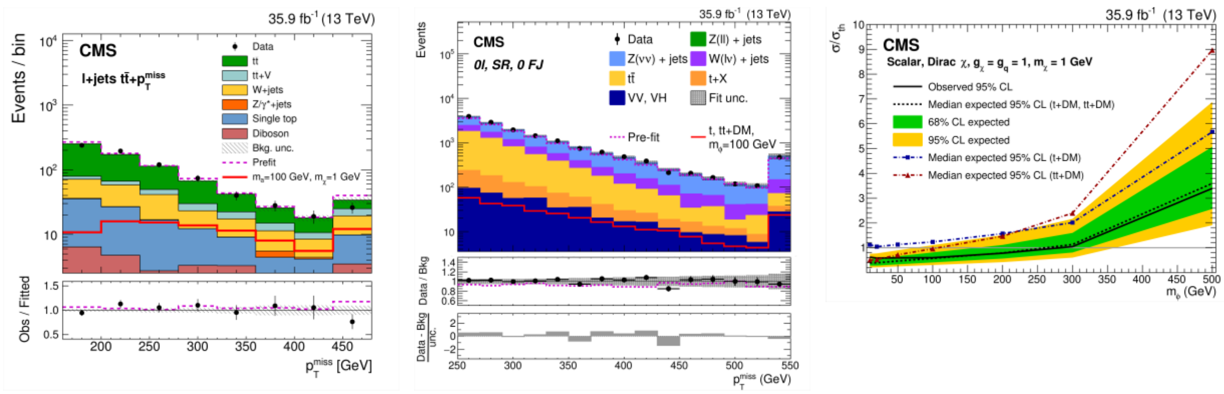


Figure 13: Missing ET distribution in the lepton+jets final state for the $t\bar{t}$+DM analysis (left), the missing ET for the sum of the t+DM and $t\bar{t}$+DM signals and the expected background in the 0-lepton final state (middle), the expected (dashed black line) and observed (solid black line) 95% CL upper limits on the ratio between the measured and theoretical cross sections for t+DM and $t\bar{t}$+DM assuming a new scalar particle (right).

2.4.6 Strongly Interacting Massive Particle Search;

Postdoc Isabelle de Bruyn (Advisor Herndon) has been working on a search for dark matter in the form of strongly interacting massive particles. This analysis explores the possibility that dark matter is indeed produced at the LHC, and that the interaction cross section with normal matter is so high that the particles are no longer WIMPs, but become so-called SIMPs, strongly-interacting massive particles, being copiously produced at the LHC and leaving observable signals in the detector. Such SIMPs will manifest themselves in the detector as jets in the calorimeter, but with no tracks from charged hadrons. The analysis probes for the first time a unique phase space and is the first search for trackless jets in CMS. The analysis of the 2016 dataset is being finalized and a publication is expected later this year.

2.4.7 Proposed Research: Dark Matter Searches

Profs. Bose and Dasu, their postdocs Deborah Pinna and Varun Sharma, and graduate students Usama Hussain (Advisor: Dasu), Jithin Sreekala (Advisor: Dasu), and Victor Shang (Advisor: Bose) will continue their strong role in Dark Matter searches. As the co-convener of the CMS MET+X group, postdoc Pinna will continue to be responsible for the review of all CMS DM analyses and will work to ensure their timely completion and successful publication.

2.4.7.1 Mono-Jet, Mono-Photon and Mono-Z Searches

Anomalously high production of missing transverse energy, compared to the SM predictions, in events with a single jet or a single photon or a Z-boson, can indicate their recoil from dark matter produced in the collision. Our initial published searches from Run-1 and Run-2 are beginning to cover important regions of the parameter space. These searches for collider-produced dark matter play a complementary role to the direct search experiments such as LUX, PandaX, Xenon and including those planned for the near future (LZ). Our group intends to pursue this line of searches with the full Run-2 data and beyond.

2.4.7.2 Invisible Higgs Decay, Mono-Higgs and Mono-Z' Searches

Higgs sector interactions with dark matter could be rather special. The current indirect constraints on the direct coupling of Higgs to the WIMP dark matter candidate, if the WIMP mass is less than half of the Higgs mass, are rather weak allowing for 10% level new physics. Using the full Run 2 dataset, we plan to pursue the invisible Higgs decay channel as well as look for anomalous production of MET accompanied by Z bosons that decay to a pair of electrons or muons. In models with a heavy Z' and two Higgs doublets, the Z' can decay to an SM-like h(125) and a heavy pseudo-scalar A, which decays invisibly. We will continue to leverage our expertise in τ physics and exploit the h(125) decay in the τ-pair channel. In other models with light Z's, low multiplicity Z' decays (pencil jets) can be seen recoiling from anomalously large MET. We anticipate that the full Run-2 dataset will provide good discovery reach for all of these channels and are keenly pursuing them.

2.4.7.3 Top + Dark Matter Searches

Pinna, together with graduate student Shang (Advisor: Bose), will take advantage of the large datasets collected in 2017 and 2018 to further extend the sensitivity of the t+DM analysis. One of the improvements involves the inclusion of events where two leptons are produced from the decay of the W bosons. For t+DM processes, this is possible only when the top quark is produced in association with a W boson. This production mode has a comparable cross section with respect to $t\bar{t}$+DM events for mediator masses above ~200 GeV, promising improvements in the current sensitivity up to a factor of two. We plan to investigate this promising final state for the first time at colliders and to develop a dedicated optimization using Deep Neural Network techniques to further enhance the search sensitivity. Another targeted improvement for the overall analysis strategy includes the use of state-of-the-art dedicated top taggers, as well as W taggers, as promising handles to reject the overwhelming $t\bar{t}$ and vector boson+jets background, providing one of the largest improvements in sensitivity for this analysis. An additional improvement in sensitivity will stem from the fact that higher statistics available in the control regions, where the backgrounds are estimated from data, will allow us to better constrain the systematic uncertainties affecting shape and normalization of the missing transverse momentum spectrum. Our group intends to pursue the above line of research with the intent to publish with the full Run 2 dataset and beyond.

2.5 Heavy-Quark Analyses

2.5.1 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. Additionally, new particles may preferentially decay into final states containing one or multiple top quarks.

2.5.1.1 Top partners

Heavy "top partners" arise in many models that attempt to solve the hierarchy problem. These top partners are expected to have masses close to the electroweak symmetry breaking scale and thus would be accessible at the LHC.

Search for pair production of top-quark partners with charge 5/3:

Former postdoc Avetisyan (Advisor: Bose) played a leading role in the 7 and 8 TeV CMS searches for a heavy top partner with charge 5/3 which decays to a top quark and a W boson [50]. Former graduate student Clint Richardson (Advisor: Bose, PhD. 2018) took over this analysis for the 2015 and 2016 datasets at 13 TeV as his thesis topic. Richardson made several improvements to maximize the sensitivity of the 13 TeV analysis. Overall, this work resulted in two papers - one on the 2015 dataset [51] and another on the 2016 dataset [52].

Search for pair production of top-quark partners in the Zt final state:

Before transitioning to CMS, Prof Black was an active contributor to the ATLAS exotics group serving as the Heavy Quark and Top (HQT) subgroup convener and overseeing and reviewing the development of all ATLAS searches for new physics with the top quark. Prof Black was also a co-author of the Particle Data Group review on dynamical electroweak symmetry breaking [53]. Former graduate student Clare Bernard (Advisor: Black) published the first direct searches for single-vector like quarks at the LHC [54] both shown in Figure 14.

2.5.1.2 W’→ tb Searches

Prof. Bose and her students have played a leading role in several searches for W’ boson resonances decaying to a top quark and a bottom quark in the lepton+jets final state. This work has resulted in two theses (David Sperka: PhD 2014 and Dylan Rankin: PhD 2018) and four publications [55], [56], [57], and [58]. The most recent effort was led by former student Rankin (now a postdoc at MIT) who worked on several analysis improvements using the 2016 dataset. Rankin reoptimized the analysis which resulted in the most stringent limits to date on the production of W’ bosons that decay to a top quark and a bottom quark [58].

Proposed research: W’->tb

Prof. Bose is mentoring UW undergraduate student Eloise Petruska who will work on an implementation of a Boosted Decision Tree (BDT) to improve the sensitivity of the W’ analysis. Rankin’s analysis, described before, was focused on the high mass region (> 1 TeV) and used an optimized set of selection criteria for that region. Discussions with theorists prompted Prof. Bose to investigate extending this analysis to cover lower masses as well. This requires improvements to the signal selection and background rejection strategies in order to deal with the larger background at lower W’ masses. Another desired goal was improving the sensitivity of the electron channel by a better optimization of the selection criteria. Tighter requirements had been imposed in the electron channel in the past in order to deal with the significantly larger multijet background in that channel. Petruska will work on implementing a BDT and improving the signal selection process. Preliminary results, from one of Prof. Bose’s former undergraduate students (Hichem Bouchamaoui) based on CMS simulation, are promising, indicating up to a 20-30% improvement in the expected sensitivity of the analysis.

2.5.1.3 Rare Single Top Production

In addition to various SM productiton channels there may be anomalous production or decays of the top quark via anamolous couplings. Before transitioning to CMS, Prof. Black with former graduate student Alex Sherman (Advisor: Black, PhD: 2018) and former postdoc Lidia Dell’Asta (Advisor: Black) worked on the first evidence for the production of a single top quark in association with a Z boson[59] with the ATLAS detector as shown in Figure 14. Dell’Asta (Advisor: Black) was the single top quark subgroup convener.

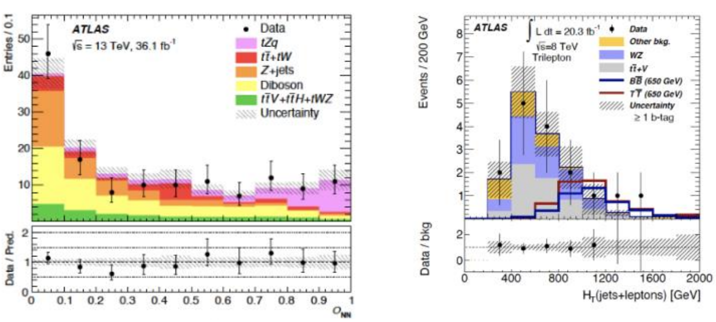


Figure 14: Example of an H_T distribution from the vector-like quark search (right) and neural network output and resulting likelihood fit (left).

2.5.2.2 Differential top quark pair production

Related other results from Prof Black during the last grant cycle while on ATLAS include the measurement of the top differential cross-section with former graduate student Clare Bernard (Advisor: Black, PhD 2014). He developed the unfolding method with Bernard and edited the paper on the top-quark differential cross-section measurement in the lepton plus jets channel published as [60] and [61].

2.5.2.3 Tri-top Production observation and searches for new physics

Prof. Black is leading the search for tri-top production with the full Run 2 dataset at CMS. SM pair production and single top production have been precisely measured both in total cross-section and many differential forms. Four top production has been actively searched for by both the ATLAS and CMS collaborations. The production of three top quarks is also possible in both the SM and in many well motivated BSM theories (associated production of a charged Higgs boson, from the decays of vector-like quarks, and various SUSY scenarios). Since the cross-section is actually smaller than four-top production in the SM because four-top production is a purely strong process, while the tri-top process necessarily includes electroweak contributions, it is a difficult signature to disentangle due to the similar final state but smaller cross-section. Teague (Advisor: Black) has developed a multivariate machine learning technique to achieve optimal separation. First results using a boosted decision tree are shown in Figure 15 which indicate promise in taking advantage of topological differences to separate and identify this small signal.

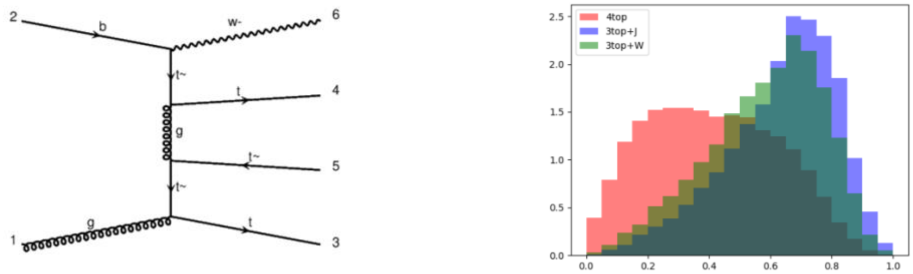


Figure 15: Example leading order tri-top Feynman Diagram (left) and preliminary BDT neural network separation of 3 and 4 top events based on topological and other event variables.

Proposed research: Tritop search

Postdoc Pinna (Advisor: Bose) will work with graduate student Dylan Teague (Advisor: Black) who has begun sensitivity studies in the trilepton and same-sign dilepton channel. Undergraduate student Runzi Li (Advisor: Black) will assist in the final state and signal optimization studies. They have begun work on developing the full event selection, trigger strategy, and background estimation with all of the Run 2 data. ML techniques will be utilized to either extract the tri-top cross-section or place limits on the SM and anomalous production modes.

2.5.2 Searches for new physics with the b-quark

2.5.2.1 Measurement of the Υ(1S) pair production cross-section and search for light resonances

Postdoc Caillol (Advisor: Dasu) was the sole analyzer of the measurement of the Υ(1S) pair production cross-section. Experimental studies of this process provide important information about the underlying mechanism of perturbative and non-perturbative processes in QCD. Quarkonium pairs can be produced either by single parton scattering (SPS) or double parton scattering (DPS) which can be experimentally separated by the topological differences in their production dynamics leading to more forward and more highly separated DPS production. In addition, anomalous production of quarkonium pairs are a signature of tetra quark production or a new light resonance with large coupling to b-quarks. Caillol utilized the four muon final state to extract the Υ(1S) + Υ(1S) signal and measure the SPS and DPS contributions to the cross-section as a function of the rapidity difference between the two upsilon candidates as well as placed limits on Tetraquark production and scalar, pseudo-scalar, and spin-2 resonances as shown in Figure 16. The paper is expected to be submitted for publication shortly.

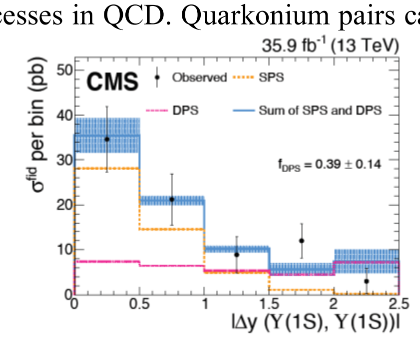


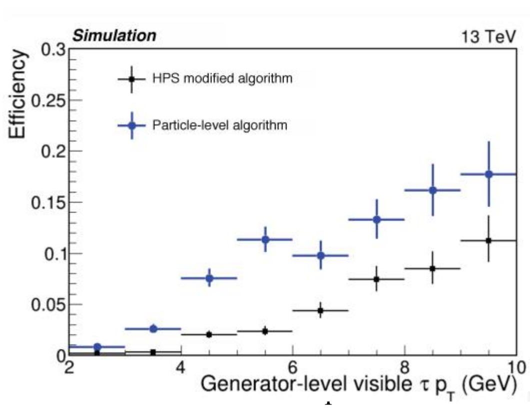
Figure 16: Υ(1S) Υ(1S) fiducial cross-section as a function of Δy.

2.5.2.2 Lepton flavor Universality measurements in B hadron decays

Decays of hadrons containing b quarks provide a powerful probe for examining the SM and one of its main principles, lepton universality, and for searching for effects of physics beyond the SM. Semileptonic decays especially, where the B-hadrons decay to another hadron, a lepton, and a neutrino, happen in the SM via tree-level processes and are an ideal setting for testing the universality of the couplings of the three charged leptons in the electroweak interactions. Recently, results from different experiments reported discrepancies with respect to the SM expectations. In particular, measurements of the parameters R(D) and R(D*) corresponding to the ratios of branching fractions of the B meson with leptonic decays in the τ and μ channels BABAR [62] [63], Belle [64] [65] and LHCb [66] show disagreement with SM predictions. Other disagreements exist, such as measurements of decays of other species of B-hadrons such as the study of semitauonic decays and a measurement of the ratio of branching fractions to J/ψ and τ or μ that was measured by the LHCb collaboration.. The measured value of 0.75 has a two standard deviation tension with the corresponding SM prediction that ranges between 0.25 and 0.28 depending on the assumptions and modeling approach chosen in the form factors calculation [67] [68].

2.5.2.2.1 Low Pt tau identification:

Postdoc Galloni (Advisor: Black) is one of the main developers of a new algorithm for the reconstruction of low p_T hadronic τ lepton decays, as explained in section 2.5.2.2.2. Galloni (Advisor: Black) served as co-convener of the Tau identification group within the Tau physics object group from September 2017 to September 2019. Under Galloni's leadership, a new deep neural network-based tau identification algorithm (DeepTau) was developed, ameliorating the performance of τ identification efficiency substantially as shown in Figure 17: at the same level of efficiency for genuine hadronic τ decays, the mis-identification probabilities for QCD jets, electrons, and muons decrease by at least a factor 2, 3, and 4, respectively [71].



2.5.2.2.2 Proposed Research: Tests of lepton universality in the b-sector and measurement of R (J/Psi)

Taus from b-hadron decays have typically transverse momenta below 5 GeV, so a new low p_T τ identification algorithm is being developed by Postdoc Galloni (Advisor: Black) and PhD student Vetens (Advisor: Black). Together they are setting up the analysis framework for the full Run 2 analysis and producing the Monte Carlo simulations for signal and background processes. The analysis will profit of the low number of additional interactions in 2016 data and of the high event statistics collected by the CMS experiment in the 2017 and 2018 data taking period, where an additional layer in the pixel detector was installed and deployed, improving the track and vertex reconstruction efficiencies. Quantities related to the vertices of the muon system, the hadronic τ decay products and their distance can be exploited to reject events where muons and tracks are produced by different interactions, ameliorating the purity of the signal in the selected data sample. It will be the first time that such an analysis is performed at CMS and the new dedicated low p_T tau reconstruction could be adapted and used in other analyses carried out by the Collaboration, especially in the light of the B-parked dataset that was recorded in 2018 with an estimated availability of billions of B-hadron decays.

2.6 Physics Analyses Service

Profs. Black, Bose, Dasu, and Herndon, and Scientists Lanaro, Klabbers, Savin, former Scientist Loveless, former postdocs Duric and Cepeda have participated in many CMS physics analysis review committees (ARCs), which scrutinize both the analysis methodology for accuracy and ensure publishable papers. Dasu and Loveless chaired over a dozen ARCs, which produced papers in exotica, Higgs and EWK physics. Dr. Loveless and Prof. Dasu are part of the CMS publication committee, where they are charged with reviewing Standard Model Physics papers. Prof. Herndon performs the job of organizing Wisconsin review for papers assigned for our Institutional Review in the publication process.

2.7 Fermilab LPC Activities

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. Most recently, in 2019, Dr. C. Caillol served as one of the leaders of the CMSDAS long exercises. Profs. Bose and Dasu have lectured on CMS physics and trigger at such schools several times. Prof. Herndon has a strong collaboration with the SMP team at the LPC and has in the past taught a workshop course on tracking and large-scale reconstruction software development while on leave at Fermilab. Prof. Dasu has organized several LPC events, collaborates with LPC scientists on trigger projects and has served on the LPC management board. Prof. Bose has served on several LPC committees including the LPC management board and collaborates with LPC scientists on physics analyses and software and computing projects. Prof. Black is engaged in several LPC activities and serves on the LPC Topic of the Week committee.

3 CMS Trigger Activity

3.1 Trigger Overview and Responsibilities

For the original LHC design luminosity of 10^{34} cm^{-2} s^{-1}, 25 inelastic collisions on average occur at each beam crossing with a frequency of 40 MHz. This input rate of 10^{9} interactions every second is reduced by a factor of 10^{7} 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 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 upgrades to the LHC now in place have exceeded the instantaneous LHC design luminosity by a factor of two, while the CMS L1 trigger rate remains limited to 100 kHz by the readout electronics. This necessitated the 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, the firmware operating the Phase-1 trigger can be upgraded as needed to further improve the trigger in Run-3. The UW group designed, built, commissioned and maintains portions of this Phase-1 trigger system and is uniquely positioned to enhance its performance through Run-3.

For the HL-LHC running, planned to start in 2026, the luminosity is planned to exceed 5x10^{34} cm^{-2} s^{-1}, necessitating 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.

Prof. Smith, considered the architect of the CMS Trigger System, as recognized by his recent APS Panofsky Award, was the leader of the successful UW trigger group. His leadership roles and responsibilities in trigger electronics are now passed to Prof. Dasu, who was responsible for the design and simulation of the original and the phase-1 L1 calorimeter trigger systems. Prof. Dasu 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, who joins the UW group from Boston, had earlier served as the CMS Trigger Coordinator, taking over from Prof. Smith. Prof. Bose's focus was on HLT system and its physics performance. Her joining the UW trigger group enhances our HLT efforts significantly. Following her next important role in CMS as its Physics Coordinator, she has recently been appointed as the Deputy Manager for the US CMS Software and Computing Project, with emphasis in optimizing the HLT output, with physics priorities in mind. Since the HLT output rate directly drives the size and scope of the computing systems needed for reconstruction and analysis, her earlier CMS-wide leadership roles in trigger and physics are critical. Planning for HL-LHC HLT is just beginning, and the UW group proposes to contribute significantly towards this effort.

UW Senior Scientist Savin, who is the Convener of the CMS Upgrade Performance Studies Group and has taken on the additional role of optimizing and characterizing the upgraded trigger system for the HL-LHC, especially the stand-alone calorimeter trigger system that the UW group has full responsibility for. 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.

3.2 Phase-1 Upgraded Calorimeter Trigger

As the LHC luminosity rose quickly in Run-2, the UW group has successfully pioneered the strategy of bringing parts of planned trigger upgrades into operation as early as possible, validating their functionality through parallel operation during data-taking. The UW group built, installed and commissioned the calorimeter trigger systems adiabatically. The original 300 UW-built VME-card Run-1 RCT, with custom high-speed backplanes and inter-crate copper connections to the UK-built GCT, are replaced by a two-layer FPGA based Upgraded Calorimeter Trigger (UCT) system. The Layer-1 of the UCT is the responsibility of the UW group. The full UCT system is in operation since 2016 handling twice the nominal instantaneous-luminosity of the LHC, while keeping the thresholds low enough to maximize statistics for Higgs and other electro-weak-scale studies. The Level-1 e/γ, τ, jet, and missing transverse energy trigger objects are computed by this system based on inputs from the CMS hadron calorimeter (HCAL) and electromagnetic calorimeter (ECAL), and the hadron calorimeter in the very forward region (HF).

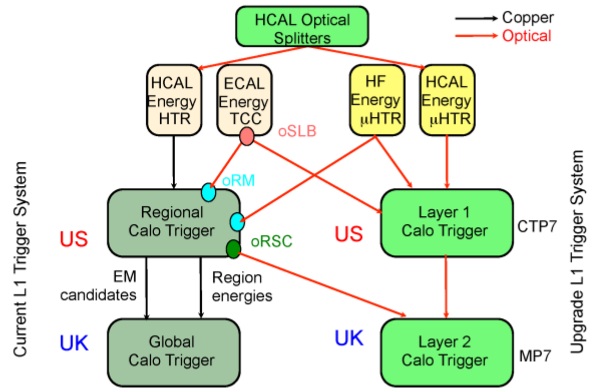


Figure 18: CT dataflow in Run-1 to Run-2.

Figure 18 Shows the splitting of ECAL and HCAL dataflow between new and old trigger systems. The upgraded ECAL provides an optical input path to the Layer-1 of the UCT, from 574 mezzanine cards (oSLB) on the ECAL Trigger Concentrator Cards (TCCs). The upgraded HCAL electronics (μHTRs) also provide optical input to the Layer-1 of the UCT.

Working with Profs. Smith and Dasu, the Calorimeter Trigger Processor card (CTP7) shown in Figure 19 was designed by UW Electronics Engineer Tom Gorski with Firmware provided by UW Engineers Ales Svetek and Marcelo Vicente (US CMS Project Supported) to implement the Layer-1 of the Phase-1 UCT. The CTP7 uses a Virtex-7 FPGA as its primary data processor. Additionally, this card design is the first in CMS to employ the ZYNQ System-on-Chip (SoC) running embedded Linux to provide TCP/IP communication and board support functions. The multi-gigabit (up to 10 Gb/s) input/output on optical fibers are located on the front side of the CTP7. Multi-gigabit inputs and outputs are also located on a custom μTCA backplane built by Vadatech to UW engineered specifications to allow data sharing.

Figure 19: CT dataflow in Run-1 to Run-2.

The Phase-1 UCT system shown in Figure 20 consists of 18 CTP7s cards distributed over 3 μTCA crates in layer 1 and 10 MP7 cards, similar to the CTP7 built by the CMS-UK group distributed over one μTCA crate in layer 2, with an optical patch panel of up to 864 fibers in between. The UW group installed 18 CTP7s, which were commissioned and are successfully operating in the CMS along with the optical patch panel since 2016. Layer-1 also captures event-by-event inputs for DAQ readout for the purpose of Data Quality Monitoring (DQM). In addition, the Crosspoint I/O Cards (CIO) that provide bi-directional access to the Vadatech VT894 backplane as well as backplane and inter-crate connections were installed.

3.3 Calorimeter Trigger Operations

The UW Layer-1 UCT operations effort is led by Senior Scientist Savin, and CMS project supported UW Electronics Engineers Tom Gorski (lead), Robert Fobes (hardware), Ales Svetek (firmware), Jesra Tikalsky (software), and involves postdocs Cecile Calliol and Varun Sharma, students Andrew Loeliger, Jithin Sreekala, Victor Shang and Abhishikt Mallampalli. Postdoc Sharma is the CMS Trigger Technical Coordinator and is responsible for operations of all of L1T. Savin and the UW team is responsible for the trigger operations at Point 5, a testing facility in Prevessin site, for repair, upgrade testing, and software development, and the large base of continuously evolving software and firmware.

We review the Layer-1 UCT performance daily to ensure it is working correctly and properly calibrated. We maintain and update lists of bad channels (either dead or mis-calibrated). We also diagnose and repair Layer-1 UCT electronics modules, cables, power supplies and system components. Since the Layer-1 UCT is a critical item for CMS during running, at least one UW expert is on call 24 hours a day.

The development of the Layer-1 UCT monitor, control, and emulation software is a UW responsibility. It was newly written with the installation of the Phase 1 upgrade. The ever-changing beam and detector conditions, operational experience, physics data and priorities and the evolving CMS software environment demand continuous effort to keep the software up to date.

The Layer-1 UCT emulator is a critical piece of the CMS software that duplicates the exact bit-by-bit function of the hardware. Essential for diagnostics and simulation of the trigger system for data quality and upgrade studies, it is constantly validated using detector data with different configurations. Postdoc Sharma (supervisor) and students Mallampalli, Sreekala and Shang maintain the emulator and check system performance with physics data, as well provide calibrations.

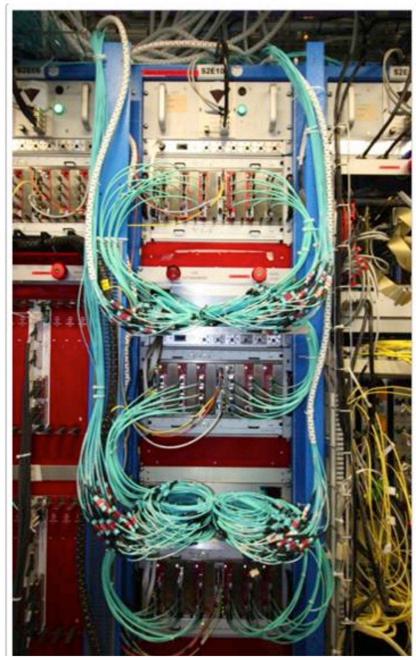


Figure 20: 3-crate UCT Layer-1.

The UW group also provided and maintains the interface between the CMS Run Control Trigger system, called SWATCH and the Layer-1 UCT. It configures (calibrations, thresholds, masked channels, etc.), starts and stops L1CT operation with the rest of the trigger systems, and processes hardware status and alarms. This software system also provides tests that load patterns into the logic and send them at speed to fully validate the Layer-1 UCT hardware. The set-up and parameters of all the programmable aspects of the Layer-1 UCT, including programmable settings and the list of masked channels masked are derived from the online Configuration Database. The actual sets of configurations loaded, the online status, including errors and alarms, and all other information about the state of the L1CT are recorded in the Conditions Database. Both of these have analogous offline databases that are interfaced to the Layer-1 UCT emulator so that it can duplicate the function of the hardware in the simulation. This task is taken by Postdoc Sharma (supervisor) and students Mallampalli, Sreekala and Shang.

The Layer-1 UCT online, offline, and stand-alone Data Quality Monitoring (DQM) was also completely rewritten by the UW group for the Phase 1 upgrade. It reads and analyzes the data as it is being taken, makes histograms, tests these against specific criteria and alerts the shift crew when there is a problem. UW group members, led by Postdoc Caillol, analyze the offline data using detailed histograms and checks to determine if the Layer-1 UCT function meets the criteria to declare the run usable for physics.

3.4 Run-3 Trigger Improvement Proposal

Since the LHC luminosity is planned to increase further or leveled at the peak for extended multi-hour operation, the UW group proposes continued development of new trigger algorithms using the Phase 1 upgrade hardware to enable the continued capture of physics signals efficiently. The eighteen-CTP7 Layer-1 of UCT has over 60% unused logic resources, enabling pre-computation of clusters as done in the RCT, in addition to continuing to serve UCT tower-level data to Layer-2. Further, the Layer-1 system has custom backplane data sharing capability and additional CTP7 slots in the crate for expansion. We plan adiabatic improvements to the calorimeter trigger (dubbed Stage-3 here), which are capable of providing unique capabilities utilizing clusters found by Layer-1. Under the direction of Prof. Dasu and UW scientist Savin, postdoc Sharma and UW students, are focusing on improving event-level analysis including VBF jets, merged-τ-pairs, merged-jets, delayed energy deposits using new calorimeter timing information and possibly muon-tagged b-jets, using muon tracks provided by the level-1 track-finders. Stage-3 firmware was implemented using High-Level Synthesis (HLS) tools from our FPGA vendor Xilinx, Inc. We propose to use these ideas for partial implementation of upgrades before the HL-LHC begins, just as we have done previously to successfully advance parts of the Phase 1 upgrade, to enable better physics reach for CMS as the luminosity steadily climbs after LS2. Potential for use of ML-based algorithms using HLS is also available. Much of this work is anticipated to be done in collaboration with Prof. Ojalvo from Princeton, who is a former graduate student and postdoc from our group.

3.5 HL-LHC (Phase 2) Trigger Upgrade

Prof. Smith co-convened the Trigger Performance and Strategy Working Group (TPSWG), which developed the CMS trigger evolution plan included in the CMS HL-LHC technical proposal (CERN-LHCC-2015-010), which he co-edited and presented to the collaboration and LHCC, which approved it. This plan calls for CMS L1 trigger to retain its present architecture, but its latency will increase to 12.5 μsec with an output of 500 to 750 kHz for pileup between 140 and 200. It will use an un-seeded L1 Track trigger along with finer granularity calorimeter and muon triggers (Figure 21).

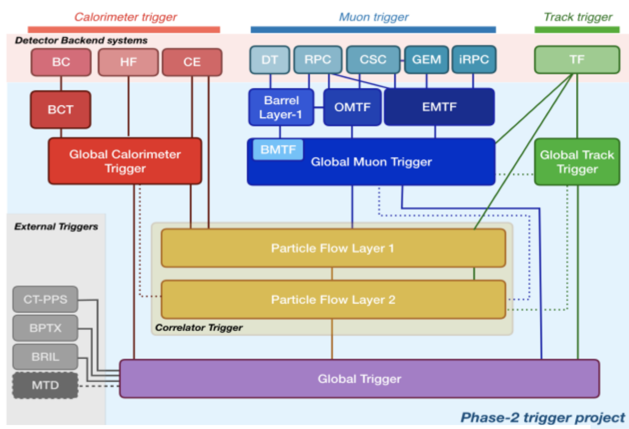


Figure 21: HL-LHC Phase 2 Trigger

Prof. Dasu is the US CMS HL-LHC calorimeter trigger upgrade L3 manager and the UW group is working on the HL-LHC calorimeter and correlator trigger projects. The calorimeter trigger (BCT & GCT) receives input data on optical fibers from the ECAL and HCAL in barrel (BC), the forward calorimeter (HF) and the high-granularity calorimeter in the endcap (CE). The granularity of both BC and EC trigger information will be 25 times greater than now, providing offline granularity information for reconstruction, isolation and position resolution for combination with tracking information. However, the 25-fold increase in CT data volume is a substantial challenge. The CT combines the information into clusters and other energy sums suitable for subsequent reconstruction as jets, electrons, photons, tau leptons, H_T and missing energy. It then provides, as output, processed trigger data to the correlator for combination with the tracking trigger and also found calorimeter trigger stand-alone objects to the global trigger. The particle flow processes data from the L1 track, calorimeter, and muon triggers and combines that information into a global event description of trigger objects, using techniques similar to those of the CMS particle flow reconstruction. The Global Track Trigger (GTT) will make trigger objects using only the L1 tracks.

Under the leadership of Senior Scientist Savin, postdoc Caillol and students Mallampalli, Shang and Sreekala are also working on the HL-LHC Calorimeter Trigger Upgrade. We have begun work on the hardware and trigger algorithms for the HL-LHC calorimeter and correlator trigger systems. We are focusing on identifying electrons, photons and taus using the new high-granularity information from the EB and HGC. This system will have reduced electron trigger rates for comparable efficiency to the present Phase 1 CT for the full EB crystal granularity CT stand-alone and combined with L1 tracking at HL-LHC luminosity. While these initial studies are promising, we plan much more algorithm development and more detailed studies as the CMS HL-LHC detector calorimetry is further developed.

We are also engaged in two specific HL-LHC hardware activities informed by the algorithm studies. After using the existing CTP7 hardware in test setups to investigate the firmware performance to implement the algorithms, evolution of the embedded Linux processing, we have moved on designing and building new prototypes based on ATCA platform.

The US CMS-supported UW engineering team of Gorski (hardware) Svetek (firmware), and Tikalsky (software) is building a series of prototypes leading towards the eventual production of electronics boards for the US-CMS HL-LHC BCT, GCT, GTT and PF Layer1 trigger subsystems. UW Scientists, postdocs and students will be involved in testing and evaluation.

The first version of the Advanced Processor (AP1) is a general purpose ATCA (Advanced Telecommunications Architecture) board with high-end FPGA (Xilinx VU9P) processor and over a hundred 25-Gbps optical links. The board will feature mezzanines and application-specific Rear Transition Modules for large memory look-up tables or a supplemental optical links, embedded linux (e.g. ZYNQ), customizable I/O capability for legacy interfaces and backplane fabrics. The Apd1 board, shown in Figure 22, has been tested extensively and is proving to be suitable for all planned trigger applications. The AP-platform is also serving as a model for backend electronics board for the calorimeter and endcap muon systems. While the first set of three Apd1 boards are already operating in the test facilities in Wisconsin and Florida, eight more Apd1 boards are being assembled to support trigger and other applications at FNAL and CERN in addition to Wisconsin and Florida. In addition to the hardware systems the UW group is also responsible for core firmware and software, while the physicists develop algorithmic firmware using HLS. The UW group physicists funded in this proposal are focusing on BCT and GCT algorithms, and are also collaborating with FNAL, Colorado and MIT on GTT and PF Layer-1 subprojects.

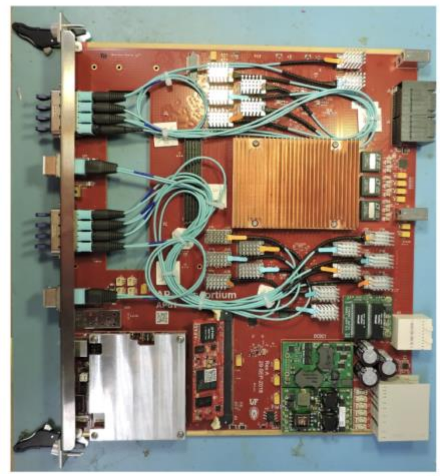


Figure 22: APD1 with Fireflys

3.6 High Level Trigger

Our group has played a leading role in CMS High Level Trigger (HLT) development and operations since the start of Run 1. Most recently, Prof. Bose served as the Deputy Trigger Coordinator (2011-2012) and as the CMS Trigger Co-coordinator (2014-2016). The latter coincided with the start of Run 2, a critical time for trigger operations. Prof. Bose's work involved coordinating the work done within the CMS Trigger Studies Group (TSG) in collaboration with the L1 Trigger group. The tasks overseen included designing trigger menus for higher luminosities, trigger code development, evaluating trigger performance and trigger menu deployment. The TSG, led by Prof. Bose, ensured the successful operation of the HLT during commissioning runs as well as the 50 ns and 25 ns collision runs. Many different trigger menus were designed covering a range of LHC scenarios: luminosities ranging from 5×10^{33} cm^{-2} s^{-1} and pileup of about 20 to 1.4×10^{33} cm^{-2} s^{-1} and pileup of about 40. Some of the highlights included the extensive use of Particle-Flow techniques at the HLT, use of "data parking" and "data scouting", use of optimized techniques for out-of-time pileup mitigation and the use of improved conditions for alignment and calibration. Dedicated menus were also deployed for special scenarios including special low pileup runs for heavy-ion, standard model and forward physics. Overall, Prof. Bose's leadership during the critical 2014-2016 period led to the successful collection of Run 2 data used for a large number of CMS publications (> 350!).

3.5.1 HLT Operations

Group members have also made several important contributions to trigger operations. Former postdoc Aram Avetisyan served as the co-convener of the Field Operations Group (FOG) within the Trigger Coordination area (2013-2015). As convener, he was responsible for the online operation of the HLT and represented the HLT/TSG in various CMS fora. Other activities overseen included: expert on-call shifts, online validation, and deployment of trigger menus. He also coordinated, in cooperation with the CMS DQM group, the development and integration of online monitoring for the HLT: online DQM, CPU and rate monitoring systems.

Avetisyan provided support for many of the commissioning runs at the start of data-taking each year and ensured that the HLT remained compatible with the upgrades to the sub-detector systems. He took the HLT expert-on-call shifts for several of the global runs and recruited and trained on-call experts for the other global runs. His other achievements included development of software for providing per-trigger HLT rates and post-deadtime Level-1 rates, development of rate monitoring software, and tools for online validation and monitoring. Former graduate students Clint Richardson (Advisor: Bose, PhD. 2018) and Dylan Rankin (Advisor: Bose, PhD. 2018) were members of the Field Operations Group and served as HLT on-call experts. They were part of a small team of CMS-wide experts providing immediate 24/7 support for any HLT issue related to operations.

3.5.2 HLT Algorithm Development and Performance Studies

Former graduate student Dylan Rankin (Advisor: Bose) spearheaded the effort for implementing jet substructure techniques at the HLT for identifying boosted top quarks and W bosons. This had never before been accomplished at a hadron collider. Rankin successfully implemented a single jet trigger using a wide jet and "trimming" to help reduce the (background) contribution from additional interactions ("pileup") while preserving signal efficiency specific to boosted hadronic topologies. Trimming is very effective against multijet/QCD events and pileup and Rankin's studies indicated that this trigger provided a significant rate reduction (~20%) over a single jet trigger with the same threshold. It became a critical trigger in Run 2 for the CMS Exotica and Beyond 2 Generations (B2G) physics analysis groups with variants of the trigger benefiting multiple analyses in different physics groups.

Former graduate student Clint Richardson (Advisor: Bose) held the responsibility for evaluating and monitoring the CPU performance of all HLT algorithms. In preparation of data-taking in 2015 and 2016, Richardson evaluated the impact of pileup on the average HLT processing time. The findings from his studies motivated significant improvements in HLT algorithms over the course of the next few years. Richardson worked on additional studies including the impact of new CMS software releases and software improvements (e.g. multi-threading) on HLT performance as well as provided feedback to the DAQ group regarding the optimal configuration of the HLT farm nodes. Richardson's critical work on HLT performance played a big role in his being awarded the 2014 Fundamental Physics Scholarship. His on-call work at CERN was thereafter recognized by a CMS Achievement award in 2016. This award is given annually to the most deserving graduate students and postdocs contributing to the sub-detector projects and data-taking/operations. Richardson was one of only six CMS graduate students who got the award that year!

3.5.3 HLT Plans for Run 3 and beyond

Postdoc Deborah Pinna (Advisor: Bose) together with graduate student Victor Shang (Advisor: Bose) will work on trigger menu preparations for Run 3. Current LHC plans include a re-start in Run 3 at either 13 TeV or at an increased center of mass energy of 14 TeV. The beam intensity will be ramped up in the LHC injectors during Run 3 and thus opens the door for long luminosity levelled fills at 2×10^{34} $cm^{-2}s^{-1}$. Such long fills with high luminosity/pileup will have an adverse impact on the total rates and increased running at high average pileup may degrade the performance of many trigger algorithms. Pinna and Shang will work on designing better performing triggers. In particular, the current missing energy triggers appear to be rather pileup dependent and require us to investigate and propose and implement solutions. Pinna will work within the TSG and evaluate trigger menu scenarios, including threshold changes, for Run 3. CMS is exploring the use of Graphical Processing Units (GPUs) as part of its HLT farm during Run 3. There are large potential benefits since certain event reconstruction tasks can be sped up more than 100 times using GPUs in comparison to conventional CPUs. Such a major infrastructural change requires extensive study and validation. Our group plans to take advantage of the GPU resources at the Center for High Throughput Computing (CHTC) at the UW and contribute to this task. Leveraging our HL-LHC L1 trigger expertise, our group also plans to participate in HLT algorithm and menu development for the HL-LHC.

4 Muon System Activities

4.1 Cathode Strip Chamber System

The UW role in the CMS Muon system project includes leadership of the Cathode Strip Chamber (CSC) forward muon system and responsibilities for chamber construction, refurbishment, integration, commissioning, operations, monitoring, performance analysis and reconstruction. In addition, the UW group is leading HL-LHC R&D on chamber longevity, operational modifications and simulation. UW Senior Scientist Dr. Lanaro was the CMS Project Manager for the CSC system from Sept. 2015 through Sept. 2019 and the US CMS Deputy EMU L2 Project Manager. UW Distinguished Scientist Dr. Loveless was the US CMS EMU L2 Project Manager for the ME4/2 project until the summer of 2014 when he retired. Prof. Herndon leads the UW CSC program, supervising Postdoc De Bruyn, former postdoc Postdoc Duric and graduate students He (Advisor Herndon), Trembath-Reichert (Advisor Herndon), Long (Ph.D. 2019, Advisor Herndon), Taylor (Ph.D 2017, Advisor Dasu) and for the period of long shutdown 2 (LS2) Sreekala (Advisor Dasu) and Vetens (Advisor Black). Prof. Herndon also serves as CSC resource manager.

1.1.1 CSC System Run 2 Operation

Following the successful construction and installation of the second disk of the ME4/2, led by Dr. Lanaro, CMS entered the Run 2 data taking period. During Run 2 (2015-2019), Dr. Lanaro, as CSC project manager, had overall responsibility for the task of maintaining stable and efficient operation of the CSC system. Jointly supervised by Dr. Lanaro and Prof. Herndon the UW CSC group continued its institutional responsibility for the monitoring of the performance of the CSC system and the validation of the quality of recorded data. From Sept. 2015 though 2017 Dr. Duric was the Detector Performance Group (DPG) coordinator responsible for “Data Monitoring and Detector Performance”, coordinating the activity of a dozen students and postdocs. Student Long was responsible for the CSC data certification and the key person in the CMS data certification team, and student Taylor the leader of the CSC prompt feedback team. Muon reconstruction efficiency, trigger efficiency, detector time and space resolution have been remarkably stable throughout Run 2, and generally exceeded that of Run 1, in spite of numerous changes to optimize the timing, synchronization and tracking algorithms.

Postdoc Duric and graduate students Taylor, Long, Trembath-Reichert and He served as Detector On-Call (DOC) experts, 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. DOC experts are the key people ensuring the successful operation of their sub-detector.

1.1.2 Offline CSC Performance studies

Starting in Run 2 UW assumed the task of offline assessment of the CSC performance. These studies were performed by Dr. Duric followed by Dr. De Bryun, and student Trembath-Reichert assisted and supervised by Prof. Herndon. Detector performance studies are focused on using tag and probe type studies of Z decays to muons to understand hit and segment reconstruction and trigger primitive efficiencies. An extensive effort was made to understand all sources of efficiency losses that reduce the detector performance under 99%. This effort has led to the identification and correction of several issues improving the efficiency of many individual CSC chambers (Figure 23). Finally, graduate student Sreekala performed additional monitoring of aspects of the system like currents which will be correlated with detector performance to understand the failure modes like Malter currents and background activity due to neutrons.

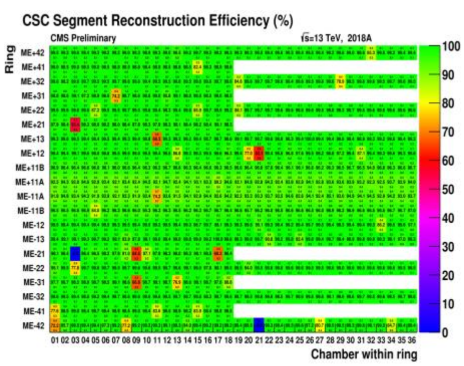


Figure 23: CSC Segment reconstruction efficiency per chamber. All ineficiencies were analyzed and understood.

1.1.3 LS2 CSC Consolidation and Upgrade for the HL-LHC

Figure 24: De Bryun and Sreekala prepare to extract a CSC chamber

For the HL-LHC, the CSC detectors are being upgraded to cope with the Level 1 trigger latency (12.5 μs) and rate (750 kHz). The readout electronics and front-end DAQ of the most forward 108 CSCs will be upgraded as was done in LS1 for ME1/1 chambers. The refurbishment of the on-chamber electronics commenced in early 2019 at the beginning of LS2. This is a large effort and required significant planning by Dr. Lanaro, as CSC project manager. The UW team at CERN works on chamber removal (Figure 24), refurbishment, testing, installation and re-commissioning. Dr. Lanaro and Dr. De Bryun primarily work on chamber removal as well participate all aspects of the project providing leadership and expertise. Dr. De Bryun serves as radiation protection officer assessing the radiation conditions of the worksite and system components, respoinsible for designing and implemeting radation safety proceedures. In addition, she serves as deputy and recently lead CSC upgrade manager. Graduate students Sreekala, Trembath-Reichert and He work on extraction, refurbishment and testing teams respectively. Graduate student Vetens is training to work on testing and commissioning.

The UW group is responsible for multiple infrastructure projects associated with the upgrade including low voltage distribution, chamber covers, thermal pads and cooling circuits. The former items were designed and fabricated at the UW physics sciences laboratory under the direction of Prof. Herndon and the low voltage distribution boxes were assembled and installed by graduate student Trembath-Reichert. In Run 2 several CSC cooling circuits exhibited leaks. To address this a long term robust solution was designed under the direction of Dr. Lanaro and is being installed on ME1/1 chambers during LS2.

1.1.4 Run 3 Commissioning and Data taking

The UW group will play a significant role in the commissioning of the upgraded CSC muon system for Run 3. Dr. Lanaro, Dr. De Bryun and newer graduate students are assuming duties in testing and commissioning in anticipation of the CSC LS2 effort transitioning to the commissioning of the full CSC system. Prof. Herndon is focusing on preparation for detailed performance monitoring using Run 3 data. The software and infrastructure used for these studies is being improved so that faster response can be achieved, especially considering the additional challenges that are likely to be encountered in recommissioning the system after LS2. The UW group will address several near-term detector operational challenges. Monitoring of the detector response will be improved with the addition of new parameters (gas monitoring, gas gain, HV and LV stability) with increased granularity and the ability to correlate these parameters with detector performance.

In summary, the UW group will play a major role in maintaining high detector efficiency for recording high quality data to be used in physics analyses throughout the lifetime of the experiment and will train the next-generation UW students and post-docs in the UW institutional responsibilities: chamber expertise, detector infrastructure, LV power distribution, on-call detector experts, data quality monitoring, detector physics performance studies and detector simulation.

1.1.5 Other CSC activities

Prof. Herndon serves as CSC muon conference committee representative. He is responsible for providing opportunities for postdocs and students to present their work at conferences and for reviewing talks and proceedings to ensure high quality. Prof. Herndon also serves and CSC resource manager responsible for manpower and budgets for the international CSC collaboration.

1.1.6 Synergistic activities with GEM

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

4.2 Gas Electron Multiplier Chamber Upgrade

While on ATLAS, Prof. Black had worked on the HL-LHC upgrade for the ATLAS muon project. This project, called the L0MDT, will both integrate the precision ATLAS drift tubes into the L0 ATLAS hardware trigger and replace the current back-end electronics. Prof. Black had been serving as the US ATLAS L3 leading the project (resource estimation, scheduling, risk mitigation and planning) and serving as the institutional contact for Boston University in collaboration with Prof. John Butler. Prof. Black was the international ATLAS wide responsible for the development of the blade and involved in the development of the segment finding firmware which contributed to the recent ATLAS trigger TDR which was accepted by ATLAS and the LHCC formally last year [72].

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

The scope of the US project includes the optical hybrid (OH) boards which collect and process data from the front-end ASICs (VFATs) , the optical links, and the ATCA back-end card which then sends the data to the endcap muon trigger finder and DAQ path. Additionally, the OH boards send the data to the CSC trigger processor. The UW group (Prof. Black) will be responsible for the development of the APD core firmware specific for the GEM backend, testing commissioning of the GEM backend, and development and implementation of the stub-finding algorithm for the ME0 detector.

4.3 GEM Operations

Postdoc Galloni (Advisor: Black) and the and graduate students Vetens (Advisor: Black) and Teague (Advisor: Black) joined the GEM project focusing on developing the software for the read-out and the calibration of the electronics of the GEM detector. Prof. Black was recently appointed as CMS Deputy GEM Run and Commissioning coordinator and will work to organize and oversee the commissioning of the GEM detectors and operations. During data taking, making sure that the proper settings for the electronics are used is of critical importance. Post-doc Galloni (Advisor: Black) is the main developer of the GEM Calibration suite. Another central feature that the PhD Student Teague (Advisor: Black) is working on is the amelioration of the monitoring software tool that will be of crucial importance while taking data, to ensure that the hardware and the software are fully functional. Data formatting status (errors, event counters, etc.), system buffer status, and link status will also be monitored, as they all provide key information in the case of system malfunction. Dr Galloni is leading the GEM DAQ operations group responsible for integration of the electronics and xDAQ software development and operations.

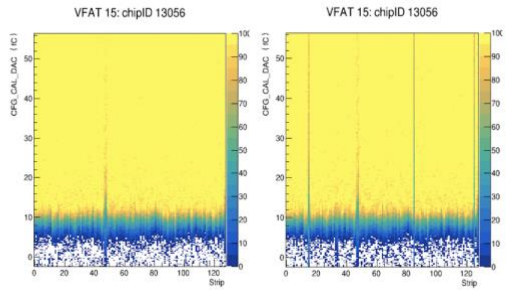


Figure 25: Value of the equivalent charge threshold of the arming DAC (S-curve) for all 128 strips of the front end ASIC shown before (left) and after (right) four induced discharges with the resistor plus diode protection: four channels have been damaged.

Galloni, Vettens, and Teague are testing the electronics of the GE1/1 detector where a external drain resistor was inserted as protection from discharges for the VFAT3 in series with an input protection circuit. Recently other protection circuit have been proposed, where the drain resistor is paired with a de-coupling capacitor or a diode and are currently under study. Two kinds of study are being performed: on a GE1/1 chamber a test stand was prepared to study the damage protection efficiency of the different proposed circuit. by creating discharges induced by alpha particles from Am_{241} radioactive decays in the detector under harsh operating conditions; on a GE2/1 chamber the effects of the different protection on the signal are being studied in terms of induced crosstalk, noise, signal efficiency, and possible signal shape distortion. An example of the first kind of study is reported in Figure 25. where the s-curves (the values of the equivalent charge threshold of the arming comparator DAC) of the 128 strips in a VFAT3 chip are reported before (left) and after (right) four induced discharges with the resistor plus diode protection: four channels have been damaged. This study will be continued in 2020.

5 Computing

The UW group operates one of the largest university-based computing facilities for HEP in the country under the supervision of Prof. S. Dasu. Prof. Bose joining the UW group, is likely to further advance our contribution to this important area as we prepare to accumulate large amounts of data in Run-3 and HL-LHC. The HEP computing 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 CMS Tier-2 computing center is supported by the USCMS Software and Computing project, an NSF grant at Princeton University. Computing services research has been conducted using direct NSF support, most recently through their Physics at Information Frontier program “Any Data, Any Time, Any Where” (AAA) grant.

The UW group also has a leadership role within the USCMS Software and Computing project. Prof. T. Bose was recently appointed to a L1-position within USCMS and serves as the Deputy USCMS Software and Computing Operations program manager. This responsibility includes oversight of USCMS facilities (Tier-1, Tier-2s, Tier-3s, networking, cybersecurity), software (including the CMS software framework and data management), operations (contributions to workflows and CMS-wide computing services) and R&D efforts towards software and computing for HL-LHC. In particular, given the budget constraints and the daunting challenge posed by the flood of data expected during the HL-LHC era, Prof. Bose is actively engaged in energizing USCMS R&D efforts for developing the computing and software systems for the HL-LHC. These efforts include, among others, adapting reconstruction algorithms to run on heterogeneous computing resources, data management tasks, and facilitating use of Machine Learning for physics analyses and operational tasks.

The US CMS project (NSF) supported researchers Drs. A. Mohapatra and C. Vuosalo, are responsible for the operation of the CMS Tier-2 facility at Wisconsin, which is a 12900-jobslot computing cluster providing 128151 HS06 units and 8.5-PB (raw) high-availability distributed storage service. In addition, Dr. Mohapatra provides operations support for exploiting opportunistic resources for CMS workflows at Open Science Grid (OSG) sites and High Performance Computing (HPC) centers. Dr. Vuosalo is responsible for maintaining and upgrading the CMS geometry description such that the most up-to-date geometry description is provided to the CMS simulation and reconstruction programs. 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 US Tier-2 sites.

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., Higgs$\rightarrow \tau\tau$, b-physics, dark matter and aTGC searches. In addition to the UW CMS team, over 50 CMS-wide users routinely use our systems either through direct login, which takes advantage of opportunistic resources (AAA), or via the OSG or the World-wide LHC Computing Grid (WLCG). Recent achievements made possible by these resources include the analysis of Run 2 data which resulted in several 13-TeV Higgs and diboson production papers and dark matter searches. On demand high priority access to resources while keeping the CPUs active with MC generation in "backfill" mode is crucial for timely completion of analyses. Close collaboration of UW CMS physicists with the NSF-supported computing team results in above average productivity.

6 Activities of UW CMS Faculty

6.1 Professor Sridhara Dasu

Prof. Dasu is involved in physics analysis, trigger operations and upgrade, and computing operations and research. He supervises Scientist Savin, Postdocs Caillol and Sharma, and the graduate students Hussain, Sreekala, Mallampalli and Tsoi, and the project supported trigger and computing personnel. Hussain transferred to Prof; Dasu due to Prof. Smith's retirement and is graduating soon.

Profs. Dasu supervises Senior Scientist Savin on SM and Higgs physics analyses, trigger operations and on designs, software and analysis of upgrades for the HL-LHC. He also supervises Postdoc Sharma on the trigger operations and offline software, on dark matter searches and exotic Higgs sector. He is also supervising Postdoc Caillol, who will soon complete her term with the group, on Higgs analyses, tau reconstruction and identification and trigger operations, online software and upgrade studies.

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

Prof. Dasu represents the UW group at the CMS collaboration meeting, taking over from Prof. Smith. He is the co-chair of the CMS Career Committee and also serves on CMS Authorship Committee. He served as the US CMS Collaboration Chair and is currently chairing the US CMS Constitution review.

Prof. Dasu played a leading role in the discovery of the Higgs boson in its decays to ZZ* with his advisee Ian Ross (Ph.D. 2013), Prof. Smith's advisee Austin Belknap (Ph.D. 2015), and Senior Scientist Savin. This program continues as this clean channel is suitable for determination of Higgs properties.

Prof. Dasu led the Higgs to tau-leptons group, which found a 3.5σ evidence for H(125) in tau-pair mode using the Run-1 data. That analysis was revised and repeated with Run-2 2016 data to obtain a 5-σ observation. The group is working on the full Run-2 analysis presently. He is also exploring the MSSM, nMSSM and potential portal to dark matter using tau-pair analyses,with his group. Prof. Dasu also searched for lepton flavor violating Higgs decays, $H \rightarrow \mu\tau$. Several graduate students had obtained their PhD degrees developing tau trigger, reconstruction algorithms and the final analysis along with the postdocs in the group. Former group members Bachtis (Ph.D. 2012, now Asst. Prof. at UCLA), Ojalvo (Ph.D. 2014, Postdoc 2014-2016, now Asst. Prof. at Princeton) and Cepeda (Postdoc 2011-2015, now faculty at CIEMAT, Spain) are successful examples.

Prof. Dasu initiated the Wisconsin dark matter search effort, with postdoc Gomber and graduate students Buchanan, Dodd and Hussain and UG students Tost and Koenig, using mono-photon, mono-Z, mono-H and mono-Z' events, accompanied by large missing transverse energy. Early papers published using 2016 data show no evidence for anomalous production of mono-objects, but there is left substantial parameter space to be explored. Postdoc Sharma is continuing to work on these analyses as Gomber moved on to a faculty position at the U. of Hyderabad, India.

The Higgs discovery and prospects for significantly improved analyses are in a large measure due to the successful measurements of the SM processes. Therefore, Prof. Dasu ensures that all graduate students and postdocs are also engaged in good quality SM measurements. Prior Run1 work on Wγ/Zγ production (Advisee Gray's Ph.D. 2012, now FNAL Staff), ZZ production including τ-lepton modes (Advisee Ross's Ph.D. 2013) is now augmented with Run2 measurements of Z(ll)Z(νν) and Z(νν)γ, as part of the dark matter searches, with postdoc Gomber and students Smith and Buchanan. With graduate student Taylor (PhD 2017), he was involved in the measurement of WZ production. Di-boson work also resulted in sensitive searches for anomalous triple gauge boson couplings.

Prof. Dasu made large contributions to the design and implementation of trigger and computing systems for CMS. He developed algorithms and wrote emulators, which were studied by former postdocs Cepeda, Friis, Ojalvo and Gomber, and are currently studied with Senior Scientist Savin, Postdoc Sharma and students Mallampalli and Sreekala.

The ambitious future physics program outlined in this proposal requires extensive improvements to trigger and computing capabilities. Prof. Dasu has taken on the task of advancing the trigger upgrade strategy for the coming years. Detailed exploration of growing complexity of the LHC data, especially moving to the HL-LHC era, demands sophistication in analysis using machine learning techniques. Several ML efforts are being started from analysis to trigger level within Prof. Dasu's group to develop and tune analyses using Run-2 and Run-3 data. On the grid-computing front, the scaling of operations to a million parallel processes, aided by GPU and FPGA accelerators is looming. Prof. Dasu intends to continue to develop systems that provide seamless global access to multi-petabyte storage systems, and location independent high-throughput computing environment.

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 Stephen Trembath-Reichert, He He and former student Kenneth Long (Ph.D. 2019) now senior research fellow at CERN. He also advises postdoc Dr. Isabelle De Bruyn and former postdoc Dr. Senka Duric . He leads the UW effort on the CMS CSC muon project, which includes his advisees and Senior scientist Dr. Armando Lanaro, graduate students Jithin Madhusudanan Sreekala (Advisor: Dasu) and Wren Vetens (Advisor: Black) and former graduate student Devin Taylor (Ph.D. 2018, Advisor: Dasu).

On the CMS experiment Prof. Herndon and his advisees have participated in multi-boson cross section measurements in WZ and ZZ at 7, 8 and 13 TeV, searches for EWK production of WZ through vector boson scattering, measurement of vector boson fusion to W and Z bosons and anomalous triple and quartic gauge coupling measurements in all of those final states. Dr. Duric primarily worked on aTGC searches included in the 8 TeV WZ paper; the 7, 8 and 13 TeV ZZ papers; and in vector boson fusion to W and Z bosons. In close collaboration with Prof. Herndon she has also developed a framework for aTGC combinations first used to produce a ZZ combination aTGC results including neutrino and charged lepton decay modes and to produce the first CMS and ATLAS combination of aTGC results. In addition, the framework is now generally used for most aTGC results in the CMS multi-boson group. This work has been expanded to combinations with Higgs results. Dr. Duric's extensive activities in the SMP multi-boson group led to her being appointed SMP multi-boson convener for 2016-1017. Long concentrated on producing the first results in WZ and ZZ production using the 13 TeV collision data and the first result in vector boson scattering and aQGC searches in the WZ mode using the 2016 data set. Long has, under Prof. Herndon's guidance, become an expert on standard model di-boson MCs and QCD issues when associated jets are produced. His expertise has led to him being appointed SMP group Monte Carlo convener, CMS matrix element and generator group convener, and, after graduating, SMP multiboson convener. Prof. Herndon new students are working on deep learning techniques to improve sensitivity to EWK production of WZ and ZZ and the polarization of the vector bosons in QCD and EWK production of WZ and ZZ. In addition, Prof. Herndon has performed several studies of the HL-LHC potential for studying EWK production. The focus on EWK production and polarization is aimed at the eventual goal of measuring the SM QGC and the extraction of the longitudinal component in massive vector boson scattering, which is sensitive to Higgs scattering of the massive vector bosons. Prof. Herndon has also led the SMP HL-LHC physics studies group and is current Rivet contact for the SMP group.

On the CMS muon system Prof. Herndon works with his advisees on online and offline monitoring of the CSC performance. Under his guidance, they have improved the detailed monitoring of the CSC hit finding and segment finding performance, implementing ideas from monitoring software Prof. Herndon designed for the CDF silicon detector. Also, in collaboration with Dr. Lanaro, Prof. Herndon's personnel have participated in the installation of upgraded electronics on the CSC chambers during LS2. They participate in chamber extraction, chamber electronics refurbishment, chamber testing and will participate the recommissioning of the full CSC system at the end of LS2. Within this effort postdoc Dr. De Bryun has been appointed CSC upgrade manager. Finally, Dr. Duric and Long participated in the setup and operation of a long-term longevity test stand for the CSC muon chambers at the GIF++ facility. This stand was used to test the instantaneous and integrated radiation tolerance of the CSC chambers under HL-LHC radiation conditions conclusively demonstrating the suitability of the CSC design for operation over the full lifetime of the HL-LHC. Prof. Herndon manages projects such as the production of physical infrastructure including low voltage distribution boxes, thermal coupling materials and chamber covers fabricated by the UW physical sciences laboratory. Prof. Herndon also serves as CSC group conference committee representative and international CSC resource manager.

In addition, Prof. Herndon also is a member of the permanent organizing committee of the yearly Multiboson Boson Interactions workshop. He also serves as US representative to the European VBSCan effort. These activities that connect the experimental and theoretical particle physics communities have given him extensive contacts with the theoretical communities engage in multi-boson physics and inform his physics research directions.

6.3 Professor Tulika Bose

Prof. Bose is engaged in physics analysis, L1 trigger and High-Level Trigger tasks, and software & computing efforts. She is currently supervising postdoc Deborah Pinna and graduate students Andrew Loeliger (H-> $\tau\tau$) and Victor Shang (Dark matter searches). During the last grant cycle, two of her students, Dylan Rankin and Clint Richardson, graduated with PhD theses on "Search for heavy resonances decaying to a top quark and bottom quark" and "Search for heavy top quark partners", respectively. Prof. Bose's postdocs and students (current and former) play important roles in L1/HLT operations/development and/or upgrade studies.

Prof. Bose has recently served as the CMS Physics Co-coordinator (PC). This was a top-level management position with a two-year term that started in September 2017 and ended on August 31st, 2019. As CMS PC, Prof. Bose was one of two lead scientists charged with reviewing the entire scientific output of the CMS experiment. She helped define the goals and types of research that collaborators undertook as they moved towards fully understanding the nature of electroweak symmetry breaking and potentially discovering new physics. She was responsible for organizing activities to produce and review all of the physics results of the CMS experiment. She oversaw all of the issues that went into ensuring that the results were correct and the best that could be produced. Under Prof. Bose's leadership, CMS submitted a record number of papers for publication with nearly $\sim$ 270 papers being submitted since the start of her stint as PC. Included in this list are some milestone measurements that Prof. Bose followed very closely such as the observation of ttH production, observation of Higgs boson decay to bottom quarks and observation of tZq production. At the same time, Prof. Bose strengthened connections with the theory/phenomenology community with invited theory talks, improved communication of physics results and successfully engaged the collaboration in a long-term physics planning effort. She also worked very effectively with the CMS trigger, offline and computing groups to ensure the most optimal use of resources for physics. The datasets thus collected will likely lead to another 100 or so publications that will be submitted in the next year.

In addition to serving as the CMS PC and supervising her postdocs and students over the years, Prof. Bose has made several other major contributions to the CMS physics effort. She served as the co-convener of the CMS Electroweak Diboson sub-group in 2011. The group was charged with measuring the WW, WZ and ZZ cross sections and also searching for anomalous trilinear gauge couplings. Understanding diboson production is important not only to further test the standard model but also for Higgs Boson searches (and measurements). In particular, WW and ZZ production form an irreducible background for many of these searches. In this context, the results obtained from the diboson cross section measurements in 2011-2012 helped validate the reliability of the techniques used in the Higgs searches culminating with the Higgs discovery in 2012. Prof. Bose then served as the co-convener of the CMS Beyond Two Generations (B2G) Resonances sub-group from July 2012 - August 2014. She also served as the USCMS Physics Liaison (2012-2014) and was responsible for representing USCMS physics interests to the funding agencies and also coordinating physics activities within USCMS. Prof. Bose was appointed as the L2 co-convener of the CMS B2G physics analysis group (2016-2017). Under her leadership, the group published a large number of papers using the 2015 and 2016 datasets.

Prof. Bose has been engaged in the CMS trigger effort since 2006. She was responsible for the HCAL trigger emulation code at the start of Run 1, played a leading role in the commissioning of the CMS HLT and as a convener of the CMS Trigger Studies Group (TSG) oversaw the successful development, optimization and deployment of trigger menus online for the 7 TeV run. She was then appointed as the CMS Deputy Trigger Co-coordinator in 2011 and prior to the start of Run 2, she was appointed as the CMS Trigger Co-coordinator (2014-2016). Prof. Bose's successful leadership of the TSG during this critical period led to the collection of a rich physics dataset that has already yielded over 350 publications!

Prof. Bose was recently recruited to take on the responsibility of Deputy USCMS Software and Computing Operations program manager. This is a L1-position within the USCMS Operations Program that leverages her expertise in physics analysis and the HLT. Responsibilities include leading an ambitious program that covers R&D efforts related to developing software and computing for the HL-LHC.

Prof. Bose was elected as an APS Fellow in 2019 for "leadership coordinating the CMS physics program and trigger system, and for contributions to the development of high level triggers and searches for heavy vector bosons and vector-like quarks". Previously, her work has been recognized by the awarding of an Alfred P. Sloan Fellowship and a CMS Distinguished Researcher award. Prof. Bose was an elected member of the DPF Executive Committee (2017-2019) and has been actively engaged in the Snowmass 2021 planning process. She is one of the co-conveners of the DOE Basic Research Needs (BRN) Study on HEP Detector Research and Development with her charge covering "Trigger and Data-Acquisition (including Machine Learning)". Prof. Bose has served on the program committee of several conferences and is one of the international co-chairs of the LHCP conference series, a major international conference for the LHC/collider community.

6.4 Professor Kevin Black

Prof Black has successfully transitioned from ATLAS to CMS with his move to the University of Wisconsin-Madison. In the last year or so, since joining CMS, he has led efforts on the development of the readout and trigger electronics for the forward GEM detector. As US L3 for the GEM upgrade project, he manages the US GEM effort consisting of a team of electronics engineers, scientists, and postdocs from UCLA, Rice Univ., TAMU, UC Davis, Florida Tech, and the University of Wisconsin. Prof. Black has leadership roles within international CMS and serves as the CMS GEM review coordinator and has recently been appointed as the CMS Deputy GEM Run and Commissioning coordinator responsible for the installation and commissioning of the GEM detectors. His students and post-docs are currently working on the xDAQ software (Galloni, Teague), electronics noise protection (Galloni, Vetens, Teague), and GEM calibration and associated software (Galloni, Teague).

Prof. Black supervises post-docs and students in the development of software and analyses ranging from the identification of low momentum taus (Galloni), tests of lepton universality in the b-sector (Galloni, Vetens), searches for rare top quark production (Pinna, Teague), and searches for di-higgs resonances (Galloni, Warden).

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. In 2014-2015 Prof. Black was honored as a US ATLAS scholar and appointed as a guest scientist at Argonne National Lab.

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 and mezzanine cards to find muon segments in drift chambers and estimate the momentum of muons leading to improved acceptance and to keep trigger rates under control during the HL-LHC. Prof. Black led the BU effort to develop the ATCA hardware blade and optical link protocol with BU taking on the role of the lead engineering institute on the project. Prof. Black was the international ATLAS L4 manager of the ATCA blade. He will leverage this experience for a similar project (ATCA back end electronics and software project) for the CMS GEM upgrade.

Prof. Black served as the ATLAS muon trigger and performance group convener for three years (2013- 2015) and supervised his post-doc (Lidia Dell'Asta) who succeeded him in this role for the following term (2015-2017). During this time period, Prof. Black's group rewrote the ATLAS L2 muon algorithms to use online tools and improved the performance and maintainability of the system. His group was also responsible for muon trigger menu development and maintained the entire suite of muon High Level Triggers (HLT). Prof. Black and his group had overall responsibility for the muon HLT for a period of approximately four years during Run 1, the first shutdown, and the first half of Run 2.

Prof. Black has successfully leveraged his experience on ATLAS and made a smooth transition to CMS where he has already assumed several leadership roles. He is, in addition, active on CMS Analysis Review Committees and is engaged within the Fermilab LPC and US CMS communities as a member of the LPC Topic of the Week committee and the US CMS Constitution committee, respectively. He is an elected member of the US LHC Users' Association (USLUA) and is co-organizing the annual USLUA and US CMS meetings being held at the University of Wisconsin-Madison in May 2020.

7 CMS & US CMS Management Responsibilities

CMS and US CMS management positions held by the UW group members are shown. We have also indicated the level of positions in the CMS or US CMS organization charts.

7.1 Current Positions

Prof. Black:	US CMS GEM Electronics Project Manager (Level-3)
	Deputy GEM Run Coordinator (Level-3)
	GEM Review Coordinator (Level-3)
Prof. Bose:	Deputy Manager, US CMS Software & Computing Project (Level-1)
Prof. Dasu:	Manager, US CMS Calorimeter Trigger Project (Level-3)
	Manager, US CMS Calorimeter Trigger HL-LHC Upgrade Project (Level-3)
Prof. Herndon:	CSC Resource Manager (Level-3)
Sen. Sci. Dr. Lanaro:	US CMS Deputy Project Manager, EMU / CSC System (Level-3)
Sen. Sci. Dr. Savin:	Co-convener, CMS Upgrade Performance Studies Group (Level-2)
Postdoc Dr. Caillol:	Co-convener, Higgs to Taus Subgroup (Level-3)
Postdoc Dr. De Bruyn:	CSC Upgrade Coordinator, CMS EMU Project (Level-3)
Postdoc Dr. Pinna:	Co-convener, Dark Matter Subgroup (Level-3)
Postdoc Dr. Sharma:	Co-Technical Coordinator, CMS Level-1 Trigger Project (Level-3)

7.2 Past Positions

Prof. Black:	US ATLAS L0MDT Upgrade Manager, Level-3 (2016-2018)
	US ATLAS Physics Support Manger, Level-1 (2016-2018)
	ATLAS Heavy Quark and Top Exotics subgroup convener, Level-3 (2013-2014)
	ATLAS Muon Trigger Coordinator, Level-3 (2012-2016)
	ATLAS Lepton+X Exotics subgroup convener, Level-3 (2006-2010)
	ATLAS Muon Commissioning Software Coordinator, Level-3 (2008-2010)
Prof. Bose:	CMS Physics Co-Coordinator, Level-1, (2017-19)
	Co-convener, CMS Beyond Two Generations Group (B2G), Level-2 (2016-17)
	CMS Trigger Co-Coordinator, Level-1, (2014-16)
	Co-convener, CMS B2G Resonances Group, Level-3 (2012-2014)
	CMS Trigger Deputy Coordinator, Level-1 (2011-13)
	Co-convener, CMS EWK Diboson Group, Level-3 (2011)
	Co-convener, CMS Trigger Menu Integration Group, Level-2 (2007-2011)
Prof. Dasu:	Chair, US CMS Collaboration Board (2014-16)
	US Regional Rep., CMS Management & Collaboration Boards (2014-16)
	CMS Upgrade Physics Coordinator (2010-11) (Level-2)
	Co-convener, CMS Electroweak Physics Group (2008-09) (Level-2)
	Co-convener, CMS Online Selection Group (2005-07) (Level-2)
	Co-convener, CMS Higgs2Taus Subgroup (2012-13) (Level-3)
	CMS Trigger and Data Acquisition Resource Manager (2012-14) (Level-3)
Prof. Herndon:	Co-convener, CMS SMP Multiboson Group (2012-13) (Level-3)
	Coordinator, SMP Future Physics and Phase 2 Studies (2015-17) (Level-4)
Sen. Sci. Dr. Lanaro:	Project Manager, CMS CSC System, (2015-2019)
	Manager, EMU Technical Coordination (Level-3)
	Co-convener, EMU Detector Performance Group (Level-3)
Sen. Sci. Dr. Savin:	Co-convener, SMP Physics Analysis Group (2014-15) (Level-2)
	Co-convener, Tau Physics Objects Group (2012-13) (Level-2)
	Co-convener, Trigger Performance Subgroup (2008-11) (Level-2)
Researcher Dr. Mohapatra:	Co-manager, CMS Worldwide MC Production (2008-15) (Level-4)
Researcher Dr. Vuosalo:	Co-Coordinator, CMS Reconstruction Software (2015-18) (Level-2)

Prof. Kevin Black– Biographical Sketch

Professional Preparation

Wesleyan University	Middleton, CT	Physics	BA, 1999
Boston University	Boston, MA	Physics	Phd, 2005
Harvard University	Cambridge, MA	Physics	2005-2008

Appointments

2018-present	Professor	University of Wisconsin-Madison
2016-2018	Associate Professor	Boston University
2010-2016	Assistant Professor	Boston University
2008-2010	Scientist	Harvard University

Products

10 most closely related to this project

1. Measurement of the production cross-section of a single top quark in association with a Z boson in proton–proton collisions at 13 TeV with the ATLAS detector, Phys. Lett. B 780 (2018) 557
2. Dynamical Electroweak Symmetry Breaking Review; K. Black, M. Narain, and S Chivukula, Particle Data Group (2017)
3. Measurement of W and Z-boson production cross-section in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector, The ATLAS Collaboration, Phys. Lett. B 759 (2016) 601
4. Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector, The ATLAS Collaboration, JHEP 04 (2015) 117
5. Performance of the ATLAS muon trigger in pp collisions at sqrt(s) = 8 TeV, The ATLAS Collaboration, Eur. Phys. J.C. (2015) 75:120
6. Measurements of top-quark pair cross-section in the l+jets channel in pp collisions at sqrt(s) = 7 TeV using the ATLAS detector, The ATLAS Collaboration, Phys. Rev. D 90, 072004, (2014)
7. Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at sqrt(s) = 8 TeV wih the ATLAS detector, The ATLAS Collaboration, JHEP 11 (2014) 104
8. Multivariate discrimination and the Higgs+ W/Z search, K.M. Black et al., JHEP 1104 (2011) 069
9. Measurement of the W->l nu and Z->ll production cross-sections at sqrt(s) = 7 TeV with the ATLAS detector, The ATLAS Collaboration, JHEP 1012 (2010) 060
10. Commissioning the ATLAS Muon Spectrometer with Cosmic Rays, The ATLAS Collaboration, Eur. Phys. J. C 70 (2010) 875-916

Synergistic Activities

1. US LHC Users Association Executive Committee (2019-2020)
2. University of Wisconsin-Madison, Physics Department Diversity Committee Chair (2019-2020)
3. US CMS and USLUA annual meeting local host (2020)
4. Outreach to high schools serving under represented minorities at Boston University (2013-2018)
5. Outreach to public high school physics teachers, Particle Physics for High school teachers program at Boston University (2012-2018)

Identification of Potential Conflicts of Interest or Bias in Selection of Reviewers

Collaborators and Co-editors (in the last 48 months):

Butler, John	Boston University
Martinez, Verena	University of Massachusetts
Gutierrez, Phil	University of Oklahoma
Taffard, Anyes	University of California, Irvine

Graduate Advisees

Bernard, Clare (Ph.D. 2014)	Broad Institute, Director of Product
Sherman, Alex (Ph.D. 2018)	Diamond Foundary, Data Analyst

Graduate and Postdoctoral Advisors

Meenakshi Narain	Brown University
John Huth	Harvard University
George Brandenburg (deceased)	Harvard University

Postdoctoral Advisees

Dell’Asta, Lidia	Senior Research Fellow, Roma Tre

TULIKA BOSE: BIOGRAPHICAL SKETCH

Education and Training:

- St. Stephen's College, Delhi University, India, Physics (Honours), B.Sc. (1996).
- Cambridge University, U.K., Natural Sciences Tripos, B.A. (1998).
- Columbia University, USA, Experimental Particle Physics, Ph.D. (2006).
- Brown University, USA, Post-doctoral training (2008).

Professional Appointments:

- Professor, Physics Department, University of Wisconsin-Madison (August 20th, 2018 – present)
- Associate Professor, Physics Department, Boston University (May 2015 - August 2018)
- Assistant Professor, Physics Department, Boston University (2008-2015)

Awards & Honors: 2019 APS Fellow, 2012 Sloan Research Fellow, 2014 CMS Distinguished Researcher Award

Recent Positions of Responsibility:

- Deputy US CMS Software & Computing Project Manager (2019 – present)
- CMS Physics Co-coordinator (2017 – 2019)
- CMS B2G (Beyond 2 Generations) Physics Group Co-convener (2016 – 2017)
- CMS Trigger Co-coordinator (2014 – 2016)
- USCMS Physics Liaison (2013 – 2014)
- Co-convener of the Resonances group within the CMS Beyond Two Generations physics analysis group (2012 – 2014)
- CMS Deputy Trigger Coordinator (2011 – March 2013)
- Co-convener of the CMS Electroweak Di-boson (WW, WZ, ZZ) group (2011).
- Co-convener of the CMS Trigger Menu Integration group (2007 – 2011).
- Lead developer and initiator of the CMS Exotica hotline. This is a novel effort designed to create a "hotline" for exotic events (2010 – 2011).

Synergistic Activities:

- Associate Editor for European Journal of Physics (EPJC): 2019-present; Reviewer for: Department of Energy, Physics Letters B, Journal of High Energy Physics, Cambridge University Press and the Netherlands Organisation for Scientific Research (NWO).
- International Co-chair for the LHCP Conference series (2019 - 2021), LHCP 2019 Program Committee member, Co-convener of Higgs and Electroweak Symmetry Breaking sessions at the 2017 DPF meeting; Co-convener of Higgs and Beyond the Standard Model sessions at the 2017 APS meeting; Co-convener of the Higgs/Electroweak sessions at LHCP Conference (2013), PANIC 2011 Program Committee member and organizer.

- Help organize and participate in activities related to Undergraduate Physics, Women in Physics and Women in Science and Engineering societies; give public lectures and interviews and interact with journalists, science writers and film makers to help disseminate information about high energy physics research to a broader audience (2006–Present).

Advisory Committees:

- Elected member of the APS Division of Particles and Field (DPF) executive committee (2017 – 2019); Member of the U.S. LHC Users Association Executive Committee (2014-2015); Elected member of the Fermilab User's Committee (2013-2015); Member of the Fermilab LHC Physics Center (LPC) Management Board (2014-2016, 2017-2019); Member of CMS Management Board (2014-2016, 2017-2019);

- Co-convener of the "Trigger & DAQ (including Machine Learning)" group for the DOE Basic Research Needs Study (2019 – present)

Collaborators: Acosta, Darin (Florida U.); Demiragli, Zeynep (Boston U.); Gutsche, Oliver (FNAL); Kaadze, Keti (Kansas State U.); Maravin Yuri (Kansas State U.); Narain, Meenakshi (Brown U.); Ojalvo, Isobel (Princeton U.).
Graduate Advisor: Evans, Hal (Indiana U.); **Postdoctoral Sponsors:** Cutts, Dave (Brown U.), Landsberg, Greg (Brown U.).
Advisees:
Postdoctoral (3 total): Pinna, Deborah: 2018-current (UW); Avetisyan, Aram: 2011-2017 (Imagine Software); Carrera, Edgar: 2009-2010 (faculty at National Polytechnic School, Ecuador).
Graduate Students (6 total): Current: Loeliger, Andrew (UW); Shang, Victor (UW); Former: Rankin, Dylan: PhD 2018 (MIT); Richardson, Clint: PhD 2017 (Tamr); Fantasia, Cory: PhD 2014 (Ab Initio); Sperka, David: PhD 2014 (BU).
Undergraduate (7 total): Petruska, Eloise (UW); Silveus, Matthew (UW); Bouchamaoui, Hichem (BU); Cheung, Elim (Univ. of Maryland); Dimitriyev, Michael (Florida Tech.); Lewin, Sylvia (Berkeley); Necib, Lina (CalTech).
Selected publications:

- CMS Collaboration, "Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV," JHEP 03 (2019) 141.

- CMS Collaboration, "Search for heavy resonances decaying to a top quark and a bottom quark in the lepton+jets final state in proton-proton collisions at 13 TeV", Phys. Lett. B 777 (2018) 39.

- CMS Collaboration, "Search for top quark partners with charge 5/3 in proton-proton collisions at $\sqrt{s} = 13$ TeV", JHEP 08 (2017) 073.

- CMS Collaboration, "The CMS Trigger system", JINST 12 (2017) no.01, P01020, arXiv:1609.02366 [physics.ins-det].

- CMS Collaboration, "Search for new resonances decaying via WZ to leptons in proton-proton collisions at $\sqrt{s}$= 8 TeV", Phys. Lett. B 740 (2015) 83.

- CMS Collaboration,"Search for top-quark partners with charge 5/3 in the same-sign dilepton final state", Phys. Rev. Lett. 112 112 171801 (2014).

- CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", Phys. Lett. B 716 (2012) 30.

Biographical Sketch – **Sridhara Rao Dasu**

Professional Preparation:

Nizam College, Osmania University	B. Sc. (Math, Physics, Chemistry) 1981
University of Hyderabad	M. Sc. (Physics) 1983
University of Rochester	M.A. (Physics) 1985, Ph. D. (Physics) 1988
Stanford Linear Accelerator Center	Research Associate, 1988 – 1992

Appointments:

University of Wisconsin	Professor, 2010 – Now, Physics Chair, 2017-21
University of Wisconsin	Assoc./Asst. Professor/Scientist, 1992 – 2010

Awards:

Fellow	American Physical Society, 2013
Vilas Associate	University of Wisconsin, 2013-15
David Dexter Prize	University of Rochester, 1987

Professional Responsibilities:

1. Chair, US CMS Collaboration, 2014-2016
2. Level-3 Manager, US CMS Trigger Operations and Phase-1 Upgrade Projects
3. Manager, CMS UW Tier-2 Computing Center, 2005-Now
4. Member, US LHC Users Association Executive, 2007-2016

Selected Publications:

1. CMS Collaboration, Observation of the Higgs boson decay to a pair of τ leptons, Phys. Lett. B 779 (2018) 283.
2. CMS Collaboration, Evidence for the direct decay of the 125 GeV Higgs boson to fermions, Nature Phys. 10 (2014)
3. CMS Collaboration, Measurement of the properties of a Higgs boson in the four-lepton final state, *Phys. Rev. D* 89 (2014) 092007
4. CMS Collaboration, Search for a standard-model-like higgs boson with a mass up to 1 TeV, Submitted for publication, Eur. Phys. J. C 73 (2013) 2469.
5. CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", Phys.Lett. B716 (2012) 30-61.
6. CMS Collaboration, "*Rates of Jets Produced in Association with W and Z Bosons production in pp collisions at* $\sqrt{s}$ *= 7 TeV*", J. High Energy Phys. 01 (2012) 010.
7. CMS Collaboration, " *Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at* $\sqrt{s}$ *= 7 TeV*", Phys. Rev. Lett. **106**, 231801, 2011
8. CMS Collaboration, "*Measurement of the Inclusive Z Cross Section via Decays to Tau Pairs in pp Collisions at* $\sqrt{s}$ *= 7 TeV*", J. High Energy Phys. **08** (2011) 117
9. BaBar Collaboration, "*Search for the Rare Decay* $B \to K \nu\nu$ ", Phys. Rev. **D82**, 112002, 2010
10. BaBar Collaboration, "*Direct CP, Lepton Flavor and Isospin Asymmetries in the Decays* $B \to K^* l^+ l^-$, Phys. Rev. Lett. **102**, 091803 (2009).

Biographical Sketch – **Sridhara Rao Dasu**

Research Program:
The primary focus of S. Dasu's research program is the study of the fundamental particles and their interactions. His contributions to the discovery of the Higgs boson and continuing efforts to acquire detailed understanding of this new particle and associated phenomena, and search for weakly interacting massive particles that can account for dark matter in the Universe, drive his research program. In the CMS experiment at CERN, he is running a diverse physics program, especially physics involving τ-leptons and Z-bosons in electroweak and higgs sectors, dark matter searches with mono-object production, trigger and computing systems design, implementation, integration and commissioning. Earlier, as a member of BaBar, SLD, E140 and E141 collaborations at SLAC and ZEUS at DESY, he made measurements that established the veracity of the Standard Model.

Synergistic Activities:
S. Dasu's experimental program requires large scale computing and sophisticated trigger electronics systems. The research and development needed for putting together these systems is an inter-disciplinary effort with computer and electrical engineering experts for exploitation of new ideas in those fields. Therefore, he runs a team in Physics and collaborates with CS teams at UW. He worked on establishing the world-wide computing grid for HEP research.
Current Collaborators: Since there are thousands in the collaborations, this selected list provided has US collaborator co-analysts and co-developers of trigger and computing:
(1) C. Jessop, Notre Dame (2) J. Conway, UC-Davis (3) F. Wuerthwein, UCSD
(4) J. Berryhill, FNAL (5) L. Bauerdick, FNAL (6) K. Bloom, UNL (7) I. Ojalvo, Princeton
Researchers and Professionals Supervised (Current & Past):
Dr. Cecile Caillol (Research Associate), Dr. Varun Sharma (Research Associate),
Dr. Sascha Savin (Senior Scientist), Dr. Armando Lanaro (Senior Scientist),
Dr. Ajit Mohapatra (Computing Researcher), Dr. Carl Vuosalo (Physics Software Developer),
Mr. Ales Svetek (Firmware Engineer), Mr. Dan Bradley (Director of Computing, UW),
Ms. Jes Tikalsky (System Administrator), Dr. Bhawna Gomber (Faculty, U.Hyderabad, India),
Dr. Pam Klabbers (Scientist, FNAL), Dr. Isobel Ojalvo (Faculty, Princeton),
Dr. Maria Cepeda (Faculty, CIEMAT), Dr. Tapas Sarangi (Industry, Madison),
Dr. Evan Friis (Software Developer, Google), Dr. Kevin Flood (IPA, DOE),
Dr. Maurizio Pierini (Staff Scientist, CERN), Dr. Jonathan Efron (Industry, Minnesota),
Dr. Monika Grothe (Industry, France), Dr. Francesca Di Lodovico (Faculty, QueenMary, UK)
Students (Current & Past):
(Physics) Mr. Abhishikt Mallampalli, Mr. Usama Hussain, Mr. Jithin Madhusudanan Sreekala
Mr. James Buchanan (PhD 2019, Data Science), Mr. Evan Koenig (BS 2019, UW UG Intern),
Mr. Marc Tost (BS 2019, GS UT-Austin), Mr. Tyler Ruggles (PhD 2018, Carnegie Institute),
Dr. Devin Taylor (PhD 2017, UC-Davis postdoc), Dr. Aaron Levine (PhD 2016, Accenture),
Mr. Stefan Cooperstein (BS, 2014, UCSD postdoc), Mr. Pingchuan Zhang (BS, 2014, Duke),
Dr. Ian Ross (PhD 2013, UW HTCondor), Dr. Lindsey Gray (PhD 2012, FNAL Scientist),
Dr. Mike Bachtis (PhD, 2012, UCLA Faculty), Dr. Mike Anderson (PhD 2011, Consultant),
Dr. Carl Vuosalo (PhD 2010, Wisconsin Tier-2), Dr. Ping Tan (PhD, 2004, Iowa),
Ms. Kendra Rand (MS, 2005), Ms. Meghan O'Connel (MS, 2005), Ms. Ada Rubin(MS, 2004)
(Computing) Mr. Vishal Mehta (2005-07), Mr. Vivek Puttabudhi (04-05),
Mr. Radhakrishna Gowrishankara Iyer (2002-04), Mr. Rajesh Rajamani (2001-02)

Prof. Matthew Herndon – Biographical Sketch

Education and Training

University of Texas at Austin	Physics	B.S.	1994
University of Maryland	Major	Ph.D.	1998
Johns Hopkins University	High Energy Physics		1998-2005

Research & Professional Experience

2012-present	Professor of Physics	University of Wisconsin – Madison
2009-2012	Associate Professor of Physics	University of Wisconsin – Madison
2005-2012	Assistant Professor of Physics	University of Wisconsin – Madison

Publications

1. [CMS Collaboration], "Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at sqrt(s) = 13 TeV," Phys. Lett. B 795 (2019) 281.
2. [VBSCan Cost Action Network Group], "Vector boson scattering: Recent experimental and theory developments," Rev. Phys. 3 (2018) 44-63
3. [CMS Collaboration], "Measurements of the pp→ZZ production cross section and the Z→4ℓ branching fraction, and constraints on anomalous triple gauge couplings at sqrt(s) = 13 TeV, Eur. Phys. J. C 78 (2018) 165, Erratum: Eur. Phys. J. C 78 (2018) 515.
4. [CMS Collaboration], "Measurement of the WZ production cross section in pp collisions at sqrt(s) = 13 TeV", Phys. Lett. B 766 (2017) 268.
5. [CMS Collaboration], "Measurement of the WZ production cross section in pp collisions at sqrt(s) = 7 and 8 TeV and search for anomalous triple gauge WWZ couplings at sqrt(s) = 8 TeV", Eur. Phys. J. C 77 (2017) 236.
6. [CMS Collaboration], "Measurement of the ZZ production cross section and Z to l+l-l'+l'- branching fraction in pp collisions at sqrt(s) = 13 TeV", Phys. Lett. B 763 (2016) 280.
7. [CMS Collaboration], "Measurements of the ZZ production cross sections in the 2 l 2 nu channel in proton-proton collisions at sqrt(s) = 7 and 8 TeV and combined constraints on triple gauge couplings", Eur. Phys. J. C 75 (2015) 511.
8. [CDF Collaboration], "Measurement of the production and differential cross sections of W+W− bosons in association with jets in ppbar collisions at sqrt(s) = 1.96 TeV", Phys. Rev. D 91, 111101 (2015).
9. [CMS Collaboration], "Search for exotic particles decaying to WZ in pp collisions at sqrt(s)=7 TeV", Phys. Rev. Lett. 109 (2012) 141801.
10. G. Benardi and M. Herndon, "Standard Model Higgs Boson Searches through the 125 GeV Boson Discovery", Ann. Rev. Nucl. Part. Sci. 61, (2011).

Synergistic Activities

1. CMS SMP Rivet Coordinator 2017-present
2. Representative CMS Muon Institutional Board 2016-present
3. International CMS CSC Resource Manager 2019-present
4. CMS CSC conference committee representative 2019-present
5. Chair of the organizing committee of the Multiboson Interactions 2016 (MBI 2016) workshop. member organizing committee 2013-present.

Collaborators and Co-editors for the past 48 months (alpha order)

Amapane, Nicola	Università di Torino, Italy
Bellan, Riccardo	Università di Torino, Italy
Charlot, Claude	Ecole Polytechnique, France, LLR
Duric, Senka	Kansas State University

Klute , Markus	Massachusetts Institute of Technology
Gomez Ceballos, Guillelmo	Massachusetts Institute of Technology
Govoni, Pietro	Universita & INFN, Milano-Bicocca, Italy
Long, Kenneth	CERN
Mozer, Matthias	Karlsruhe Institute of Technology, Germany
Pigard, Philipp	Ecole Polytechnique, France, LLR
Salfeld-Nebgen , Jacob	Massachusetts Institute of Technology

Graduate and Postdoctoral Advisors

Jawahery, Hassan	University of Maryland
Barnett, Bruce	Johns Hopkins University

Postdoctoral Advisees

De Bryun, Isabelle (2019-present)	Postdoctoral Researcher, University of Wisconsin, Madison
Duric, Senka (2012-2018)	Postdoctoral Researcher, Kansas State University
Pursley, Jennifer (2008-2010)	Research Scientist, Harvard Medical School

Graduate Advisees

He, He (2018-present)	Graduate student, University of Wisconsin - Madison
Trembath-Reichert, Stephen (2017-present)	Graduate student, University of Wisconsin - Madison
Long, Kenneth (Ph.D. 2019)	Senior Research Fellow, CERN
Parker, William (Ph.D. 2014)	Postdoctoral Researcher, University of Maryland
Klukas, Jeff (Ph.D. 2012)	Industry: Epic Systems
Jason, Nett (Ph.D. 2010)	Postdoctoral Researcher, Texas A&M University

Advisory Committees on which you serve

CMS Muon Institutional Board	CMS Experiment
CMS Conference Committee	CMS Experiment
CMS Resource Management Board	CMS Experiment
CDF Editorial Board	CDF Experiment

CMS at the LHC: Research Scientists

1 Dr. Armando Lanaro

This proposal is to support UW Senior Scientist Dr. Armando Lanaro 25%, with the remaining support coming from the US CMS Research Program Operations budget. Dr. Lanaro main duties are to be responsible at CERN for the maintenance and operation of the Endcap Muon System of CMS, its infrastructure and future upgrades, to participate to physics analysis related to the Muon System and supervise UW students in their experimental work and for the fulfillment of the PhD requirements.

From Sept. 2015 to Sept. 2019 Dr. Lanaro was the CMS CSC Project Manager. One of his major achievements during Run 2 (2015-2018) was to establish optimal reconstruction and trigger performance of EMU system upgraded with 72 new ME4/2 chambers and new electronics for the ME1/1 chambers. The completion of full CSC coverage in CMS forward muon station 4 has increased trigger efficiency and considerably improved muon p_T assignment as well as offline muon tracking and background rejection at higher luminosity and pile-up rates. Dr. Lanaro coordinated the construction of the ME4/2 chambers at CERN in 2010-2014. He led a large team (~20 people) from several collaborating Institutes: CERN, IHEP Beijing, PNPI St Petersburg and US Universities (UCLA, UCR, UF, UW, NWU, UCSB). The project was successfully completed on-schedule and the new CSCs were installed in CMS in 2013 and 2014, during the Long Shutdown 1 (LS1).

The new ME1/1 chamber and front-end electronics have improved local muon triggering and rate capability in the most forward region, where particle occupancy is highest. Moreover, the finer read-out granularity and improved electronics have increased capacity for data rate and reduced ambiguity in low-p_T muon reconstruction. Dr. Lanaro coordinated the ME1/1 chamber reinstallation, integration and commissioning in CMS.

Given the increasing LHC luminosity during Run 2, Dr. Lanaro has led a program to improve the offline reconstruction (new hit and segment reconstruction algorithms), the online (DAQ robustness, speed, slow controls) and the electronics firmware (SEU mitigation, device monitoring) system services with the involvement of many physicists and engineers from both the CSC Operation and the Detector Performance teams. Most importantly, Dr. Lanaro has promoted and coordinated an effort to improve the data quality monitoring, also adopting frontier machine learning techniques, with the aim of deriving reliable predictions for the detector response to the harsher conditions expected from Run 4 onward when the High Luminosity LHC (HL-LHC) will start operating.

Furthermore, Dr. Lanaro has led the effort to establish the best strategy for the consolidation and upgrade of the CSC system for the HL-LHC and CMS Phase 2 upgrade. The conditions imposed by the HL-LHC on the CMS trigger rate (750 kHz) and latency (12.5 μs) will significantly impact the electronics functionality of the most forward CSC rings, requiring their replacement. Dr. Lanaro has worked with engineers from OSU, TAMU, NEU, UCSB and UCLA, to design and oversee construction of a robust electronics system for sustained operation at the HL-LHC. The current (2019-2021) LHC Long Shutdown 2 (LS2) provides an opportunity to install the new electronics on the 180 CSCs, at the highest pseudo-rapidity, which will be the most exposed to the high background radiation of the HL-LHC. This huge effort refurbishment 2019-2020, will be followed by final system re-commissioning before the start of Run 3 in the early summer of 2021.

During his mandate as CSC project leader, Dr. Lanaro, as member of the CMS Muon Management Board to establish a coherent Muon system Phase 2 Upgrade program which comprises new detectors to enhance the physics reach while improving and preserving the functionality of present muon detectors. After contributing to the 2015 CMS Phase 2 Technical Proposal, Dr. Lanaro has played a key role in the preparation of the 2017 Muon Upgrade Technical Design Report [6].

For the consolidation of the present EMU detector system, Dr. Lanaro has proposed and led an approved R&D program since 2014 for performing longevity studies of irradiated CSCs in order to detect early signs of aging after accumulating the dose expected after 10 years at the HL-LHC. The project has progressed steadily at the CERN new Gamma Irradiation Facility (GIF++) where two CSCs, of different types, have been exposed to intense gamma irradiation since early 2016. Dr. Lanaro has coordinated all operations from installation of detectors and infrastructure to setting up the data recording system and the definition of procedural protocols for stability monitoring during irradiation. A crucial requirement has been to setup a system identical to the one operated in CMS (detectors, DAQ, trigger and gas systems, electronics, environment parameters), thus making testing at GIF++ a realistic representation of the intense HL-LHC background environment. The irradiation campaign was completed in 2018 after collecting an accumulated dose equivalent to 3000fb^{-1} of data at the HL-LHC, with a safety factor 3. No hints of performance degradation were observed, thus proving that CMS CSCs design is very robust against aging. The contribution to the project of UW postdoc S. Djuric and graduate student K. Long was outstanding.

As part of the EMU consolidation program, Dr. Lanaro is investigating further improvements, both to anticipate future requirements in detector operation as well as to explore the possibility to reduce the EMU operation cost. The CSC system operates with a 3-component gas mixture: Ar(40%)-CO_2(50%)-CF_4(10%). Future EU restrictions on the use of CF_4, which is a potent greenhouse gas, may possibly lead to shortfall or gas cost escalation. Dr. Lanaro was then inspired to start an R&D program on the search and testing of eco-friendlier substitutes for CF_4 or, in alternative, on the operation of the CSC system with a reduced fraction of CF_4 in the gas mixture.

The extensive knowledge and multi-year experience of Dr. Lanaro as CMS CSC Field Technical Coordinator and CSC Project Manager make him the most expert person to tackle sudden issues impacting EMU operation (water leaks, gas parameter instability, aging of system components) or constituting a potential threat to general safety or to CMS stable running. As an example, a water leak that occurred in one ME1/1 chamber in Nov. 2015 had consequences for CMS stable running and caused some collateral damage to other sub-systems in CMS. This had to be addressed and solved promptly by Dr. Lanaro and his co-workers. The follow-up of this incident has required Dr. Lanaro and his collaborators from Dubna Institute to search for suitable technical solutions and propose long-term mitigation strategies to the CMS Technical Incident Panel. The newly design circuits, which are currently been fitted to the ME1/1 chambers, provide a risk-free solution of a long standing issue.

During daily CMS running, Dr. Lanaro supervises the task of maintaining stable and reliable operation of the EMU system with minimal downtime to CMS data recording while ensuring adaptability to rapidly changing conditions (from CMS and LHC). Drawing on his past experience as CSC Detector Performance Deputy Coordinator, Dr. Lanaro, in collaboration with his UW colleague, Prof. M. Herndon, have been leading system operational feedback and investigation of the physics performance from analysis of collision data. UW students (Gray, Taylor, Long, He, Trembath) and postdoc (Djuric, De Bruyn) have been participating in this effort in past and recent years.

Dr. Lanaro has broad and unique experience with leading the CSC chamber installation and extraction off the CMS endcap disks and all aspects of chamber handling. The training that Dr. Lanaro has being providing to UW postdoc De Bruyn has been particularly fruitful in preparing her for the positions of responsibility she now occupies, and especially her position as CSC Upgrade coordinator since September 2019.

Since 2013 Dr. Lanaro has been the USCMS Deputy L2 Operation Manager working with the L2 Manager Prof. Darien Wood (NEU) in the preparation and submission of the yearly EMU Operation funding requests, assembly of timely reports to the US-CMS Management and funding agencies.

In his 16 years participation in EMU, Dr. Lanaro has actively taught students the working principles of modern gas detectors and guided them through their construction and operation. He has developed their teamwork skills, taught how to share responsibility and deliver high quality projects. He has been advising on experimental detector research and physics analysis related to muon triggering, identification and reconstruction and on the methodology for establishing performance parameters of a detector system, like efficiency, time and space resolution. Some of his former students, both from UW and elsewhere, are now well-established scientists.

Biographical Sketch - Dr. Armando Lanaro

Education and Training

University of Rome (Italy)	Physics	B.S.	1982
University of Rochester	Physics	M.S.	1984
University of Rochester	Physics	Ph.D.	1989

Research & Professional Experience

2015-present	Senior Scientist	CMS	U. of Wisconsin - Madison	CMS CSC Project Manager (until Sept 2019) responsible for CSC Operation and Upgrade and US-CMS Deputy L2 Operation Manager
2008-2015	Associate Scientist	CMS	U. of Wisconsin - Madison	EMU Upgrade Manager responsible for the ME4/2 Chamber Factory at CERN. Coordinator for detector performance studies and improvements. Member of the CMS Quarkonia and Zγ Physics analysis groups
2003-2008	Assistant Scientist	CMS	U. of Wisconsin - Madison	EMU L3 Manager and CMS CSC Field Technical Coordinator responsible at CERN for the installation, integration and commissioning of the CSC Muon system in CMS

Publications (most closely related to this project)

1. Search for a narrow resonance lighter than 200 GeV decaying to a pair of muons in proton-proton collisions at $\sqrt{s}$=13 TeV

CMS Collaboration (Albert M Sirunyan et al.). Dec 10, 2019. **e-Print: arXiv:1912.04776**

2. Search for the Higgs boson decaying to two muons in proton-proton collisions at $\sqrt{s}$=13 TeV

CMS Collaboration (Albert M Sirunyan et al.). Jul 17, 2018. **Phys. Rev. Lett. 122 (2019) no.2, 021801**

3. Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s}$=13 TeV

CMS Collaboration (Albert M Sirunyan et al.). Apr 12, 2018. **JINST 13 (2018) no.06, P06015**

4. Search for *Zγ* resonances using leptonic and hadronic final states in proton-proton collisions at $\sqrt{s}$=13 TeV

CMS Collaboration (Albert M Sirunyan et al.). Dec 8, 2017. **JHEP 1809 (2018) 148**

5. Measurement of quarkonium production cross sections in pp collisions at $\sqrt{s}$=13 TeV

CMS Collaboration (Albert M Sirunyan et al.). Oct 30, 2017. **Phys. Lett. B780 (2018) 251-272**

6. The Phase-2 Upgrade of the CMS Muon Detectors. Technical Design Report

CMS Collaboration (Albert M Sirunyan et al.). Sep 12, 2017. **CERN-LHCC-2017-012 CMS-TDR-01**

7. Measurement of the *Zγ* Production Cross Section in pp Collisions at 8 TeV and Search for Anomalous Triple Gauge Boson Couplings

CMS Collaboration (Vardan Khachatryan et al.). Feb 19, 2015. **JHEP 1504 (2015) 164**

8. Technical Proposal for the Phase-II Upgrade of the CMS Detector

CMS Collaboration (CERN-LHCC-2015-010; LHCC-P-008; CMS-TDR-15-02)

9. Measurement of the Wγ and Zγ inclusive cross sections in *pp* collisions at $\sqrt{s}$=7 TeV and limits on anomalous triple gauge boson couplings

CMS Collaboration (Serguei Chatrchyan et al.). Aug 30, 2013. **Phys. Rev. D89 (2014) no.9, 092005**

10.The performance of the CMS muon detector in proton-proton collisions at $\sqrt{s}$=7 TeV at the LHC
CMS Collaboration (Serguei Chatrchyan Inst. et al.). Jun 28, 2013. **JINST 8 (2013) P11002**

Collaborators and Co-editors (in the last 48 months):

CMS Collaboration

Graduate Advisees

He, He	UW grad student
Madhusudanan Sreekala, Jithin	UW grad student
Trembath-Reichert, Stephen	UW grad student
Long, Kenneth	UW grad student
Gray, Lindsey	UW grad student

Graduate and Postdoctoral Advisors

Ferbel, Thomas	University of Rochester

Postdoctoral Advisees

De Bruyn, Isabelle	UW post-doc
Djuric, Senka	UW post-doc

Advisory Committees

None

CMS at the LHC: Research Scientists

1 Dr. Alexander (Sascha) Savin

This proposal is for full support of UW Senior Scientist Dr. Sascha Savin.

Dr. Savin is serving as the Upgrade Performance Study Group (UPSG) co-convener. The UPSG is a group jointly under Upgrade Coordination and Physics Coordination. It oversees studies of physics cases relevant for the Phase II Technical Design Reports (TDRs) and provide input for any detector design optimizations. This includes defining the physics benchmarks to evaluate the performance of the specific upgrade elements. The conveners, with the help of Offline & Computing, Physics Performance and Trigger Coordination also oversee software development for Phase II reconstruction in the CMS software framework. This implies software development, validation and Monte Carlo production. The studies are 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. The group has three subgroups: one responsible for Higgs and SM related studies, a group that covers all possible physics subjects beyond SM and a group that provides technical support for users, analyses framework and MC validation tools. UPSG has also contacts in PAGs and POGs, and representatives in Physics Performance and Dataset (PPD), validation and generator groups. This structure allows UPSG to effectively resolve all tasks related to the group mandate. The group has approximately 50 permanent members, the number increases when working on TDR preparation or other tasks.

In the period September 2016 - September 2018 Dr. A.Savin was Future Standard Model sub-convener in UPSG working on selecting a set of important measurements for the Phase II, defining necessary requirements for the detector subcomponents and documenting all the results in different CMS Technical Design Reports. Dr. A.Savin participated in preparation of the Yellow Report in 2018 [2,3]. The Yellow Report is a summary of the physics goals for the HL-LHC upgrade and includes contributions from both CMS and ATLAS experiments, as well as theoretical contribution to future studies. Among other physicists and Ph.D. students the group included UW Postdoc C. Calliol and UW Ph.D. students N. Smith and U.Hussain.

From September 2018 Dr. A.Savin serves also as EGamma co-convener of the L1 Trigger TDR. Together with UW PhD students T. Ruggles and V.Shang, and UW PostDocs C.Calliol and V.Sharma he is developing a new trigger strategy for Calorimeter Trigger HL-LHC upgrade, based on the crystal segmentation of the electromagnetic calorimeter and combination with tracking information. He led a preliminary study of simulated EGamma trigger performance showing a significant improvement, by a factor three to four, of the trigger spatial resolution and a factor of 10 decrease in the trigger rate with respect to the existing design, if calorimeter and tracker information will be combined for EGamma reconstruction. This improvement is essential for operation of the CMS detector in the high pileup and high luminosity environment at the HL-LHC. Recently this work was extended to the jets and tau reconstruction. As a result of the work of the group of UW PostDocs and Ph.D. students the whole trigger reconstruction chain for the Phase II Barrel Calorimeter trigger was developed, simulated and is used in the L1T TDR that is due in Q2 2020. The hardware/firmware implementation was also performed together with UW engineers T. Gorski, A, Svetek and M. Vicente to prove the functionality of the triggers in the real prototype and was documented in the L1T TDR. Dr. A.Savin contributed to development of the L1 trigger architecture that allows to combine all calorimeter information for calorimeter-only triggers or to combine it with other trigger systems. This work, initiated by Dr. Savin and driven by UW, currently involves Ph.D. students and physicists from three other Universities.

It is essential that for the HL-LHC upgrade program the Machine Learning techniques will be used. The recent firmware and hardware developments allow to use it even for L1 trigger. From the analyses point of view this techniques was already used recently Deep Neural Network (DNN) is studied for the full Run 2 analysis of the electroweak (EW) ZZ production. In this analysis Dr. A.Savin and UW Ph.D. student H.He are using DNN approach to increase the expected significance of the EW signal observation. DNN techniques will be used also in analysis of Run 3 data. Similar techniques are under development for Phase II L1 and should help to reduce the trigger rate with almost no loss in the signal events.

Dr. Savin personally contributed to an exceptionally large number of CMS physics analyses. Dr. Savin led a group on the first measurement of the WZ cross section at 13 TeV (approximately 15 members)[8] where he worked together with UW PhD student D.Taylor. Recently together with UW Ph.D. student K.Long the next WZ paper on vector boson scattering was published [1]. This is the first WZ VBS measurement in CMS. Dr. Savin is a key component of our future plans in muli-gauge boson physics where he will provide supervision and analysis expertise on the subjects of vector boson scattering in ZZ and WZ final states and, searches for WWW production in leptonic decay modes along with anomalous coupling searches in both analysis. Also this physics effort is directly connected to future physics studies of the potential of those final states.

During the next three years, Dr. Savin plans to study properties of 4l final states together with UW Ph.D. students U.Hussain and H.He. The goal for 2020-2022 is to measure different properties of the Higgs boson using its decay to ZZ to 4l, measure inclusive and differential cross sections of the non-resonant ZZ production to investigate ZZ vector boson scattering and polarization processes. The program also includes searches for high mass resonances and for anomalous gauge couplings. While the Higgs ZZ group consists of about 60 members, the measurements of inclusive and differential ZZ cross sections and limits on anomalous coupling at 7, 8 and 13 TeV were driven by UW under Dr. Savin's supervision and with help of UW PhD students and Postdocs and were documented in [4,5,9,0]. Dr. Savin is a coauthor of all publications on Higgs searches in the ZZ to 4l decay channels [6,10].

Together with UW Ph.D. students L.Dodd and T.Ruggles Dr. Savin studied Higgs production in the 2 lepton modes, including Higgs to $\mu\mu$ and $\tau\tau$ production. In 2017-2018 Dr. Savin and the UW group studied Higgs decays to $\tau\tau$ in a wide region of visible masses. The full statistics of 13 TeV data allowed for observation of the Higgs decay to two tau leptons [7]. Dr. Savin has a long record of tau-related tasks since he participated in development of algorithms for reconstruction of tau-leptons in their hadronic decays that is currently used in all CMS analyses. In 2018 he led the tau algorithm development task force for Phase II analyses, the proposed algorithm was used in the HL-LHC Yellow Report studies.

In 2014-2015 Dr. Savin led the second largest CMS Physics group – the Standard Model Physics Analysis group (approximately 350 physicists and PhD students, up to 50 ongoing analyses). Under his supervision, the group started 36 new physics analyses, published 22 analyses and at the end of 2015 a further 15 analyses were close to be published.

Dr. Savin leads the UW team of Postdocs and students bearing the responsibility for the calorimeter trigger operations at Point 5, a testing facility at Prevessin, for repair, upgrade testing, and software development, and the large base of continuously evolving software and firmware.

Biographical Sketch - Dr. Alexander (Sascha) Savin

Education and Training

Undergrad Institution: Moscow State University	Cosmic ray experiment at mountain level, search for heavy particles in cosmic rays	Diploma in Physics	1989
Graduate Institution: Moscow State University	ZEUS experiment, Hadron-Electron Separator group	PhD in Physics	1993
Post Doc Institution: DESY	ZEUS experiment, Hadron-Electron Separator group, vector-meson production		1994-2000

Research & Professional Experience

2015-present	Senior Scientist	CMS	University of Wisconsin – Madison	Upgrade Performance Study Group convener; EGamma L1 TDR convener ; CMS Standard Model Physics group convener
2006-2014	Associate Scientist	CMS	University of Wisconsin – Madison	Tau-lepton object group convener ; Trigger performance group manager ; calorimeter trigger DQM responsible
2000-2005	Assistant Scientist	ZEUS	University of Wisconsin – Madison	QCD group convener; Calorimeter Trigger Coordinator ; Local leader of the UW group

Publications

1. CMS Coll., Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at sqrt(s) = 13 TeV, Phys. Lett. B 795 (2019) 281
2. P.Azzi, …A.Savin.., et al. , Standard Model Physics at the HL- LHC, arXiv:1902.04070
3. M.Cepeda, …A.Savin.., et al., Higgs Physics at the HL-LHC, arXiv:1902.00134
4. CMS Coll,. Measurement of differential cross sections for Z boson pair production in association with jets at sqrt(s) = 8 and 13 TeV, Phys. Lett. B 789 (2019) 19
5. CMS Coll., Measurements of the pp to ZZ production cross section and the Z to 4l branching fraction, and constraints on anomalous triple gauge couplings at sqrt(s) = 13 TeV, Eur. Phys. J. C 78 (2018) 165
6. CMS Coll., Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at sqrt(s) = 13 TeV, JHEP 06 (2018) 127
7. CMS Coll., Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector, Phys. Lett. B 779 (2018) 283
8. CMS Coll., Measurement of the WZ production cross section in pp collisions at at sqrt(s) = 13 TeV, Phys. Lett. B 766 (2017) 268
9. CMS Coll., Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at sqrt(s) = 13 TeV, Phys. Lett. B 774 (2017) 682
10. CMS Coll., Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at sqrt(s) = 13 TeV, *JHEP 11 (2017) 047*

Collaborators and Co-editors (in the last 48 months):

CMS Collaboration

Graduate Advisees

Long, Kenneth (Ph.D. 2019)	
Taylor, Devin (Ph.D. 2018)	
Woods, Nate (Ph.D. 2018)	
Perry, Tom (Ph.D. 2016)	
Ross, Ian (Ph.D. 2013)	UW Computer Science
Swanson, Joshua (Ph.D. 2013)	
Bachtiks, Michalis (Ph.D. 2012)	UCLA, Assistant Professor

Graduate and Postdoctoral Advisors

Bashindzhagyan, George Moscow State University

Postdoctoral Advisees

Sharma, Varun (20xx-20xx)	Current
Caillol, Cecile (	Current
Djuric, Senka	

Advisory Committees

N/A

Current and Pending Support
KEVIN BLACK
1/22/20

Current:

Project:	High Luminosity LHC U.S. CMS Detector Upgrade
Source:	Princeton (NSF) SUB0000186
Total Award:	$ 427,664 Period: 01/01/19-12/31/25
Location:	CERN, UW-Madison
Abstract:	The group contributes to the activities within the US scope of the CMS HL-LHC forward muon upgrade. The scope of the US CMS HL-LHC Muon upgrade project includes management tasks, as well as two main technical areas: upgrade of the data acquisition system for the Cathode Strip Chambers (CSC) detector system and construction of the elements of the electronics DAQ system for the muon Gaseous Electron Multiplier (GEM) detectors. Management scope includes support for management and system engineering tasks. The main components of the CSC upgrade includes design and construction of the Optical Data Motherboards (ODMB) processing data from individual CSC chambers, the backend (FED) system based on Advanced TeleCommunications Architecture (ATCA), which includes crates, DAQ and timing hub boards and high-power/high-bandwidth processing boards (one of the Compact Muon Solenoid (CMS) standard boards), and optical links connecting the ODMB with the backend electronics. GEM upgrade includes construction of the following items for the GE2/1 and ME0 GEM detectors DAQ/Trigger systems: the on-chamber Optohybrid (OH) Boards, an ATCA-based backend electronics setup: crates, DAQ and timing hub boards and high-power/high-bandwidth processing boards, and optical links connecting the OH with the backend electronics. Signals processed by the backend electronics will be transferred to the central CMS DAQ system and the Endcap Muon Track Finder (EMTF). In addition to electronics, each of the systems includes development of firmware and control software elements. Elements of the forward muon upgrade scope that the University of Wisconsin-Madison group is engaged in is as follows: *Project Management:* Professor Kevin Black serves as the Level-3 Manager of the US CMS HL-LHC Forward Muon Upgrade responsible for the oversight of the GEM scope, documentation, cost estimation, scheduling, and progress monitoring. *ME0 Backend Firmware Development and Integration:* The University of Wisconsin-Madison contributes to the development of control firmware and software on the ME0 backend and is a lead institution for the development and implementation of the algorithm for the stub finding on the ME0 that will then be combined with information from the EMTF to form the final endcap muon trigger. The group also contributes to the tasks related to integration of the ME0 backend with the rest of the GEM DAQ system.

Pending:

Project:	High Energy Physics Research: CMS @ LHC (shared with Bose, Dasu, Herndon)
Source:	DOE (this proposal)
Total Award:	$ 4,296,445 Period: 04/01/20-03/31/23
Location:	CERN, UW-Madison

Current and Pending Support
KEVIN BLACK
1/22/20

Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00

Abstract: Prof Black will lead the Gas Electron Multiplier GE 1/1 run and commissioning, develop and maintain the calibration and monitoring of the GEM detectors, and be responsible for the development and integration of the back end GEM electronics. In addition, Prof Black will lead his group in physics analysis on the search for new physics with top quarks, top quark properties, b-flavor anomalies, and searches for new resonances decaying into pairs of Higgs bosons.

Current and Pending Support
TULIKA BOSE
1/22/20

Current:

N/A

Pending:

Project: High Energy Physics Research: CMS @ LHC (shared with Black, Dasu, Herndon)
Source: DOE (this proposal)
Total Award: $ 4,296,445 Period: 04/01/20-03/31/23
Location: CERN, UW-Madison
Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00
Abstract: Prof. Bose's research thrust in this proposal covers analysis of the full Run 2 dataset in a number of areas including Higgs Boson measurements, searches for dark matter candidates, and searches for new physics with top quarks. She supervises postdoc Deborah Pinna and two students, Andrew Loeliger (Higgs -> $\tau\ \tau$) and Victor Shang (dark matter searches). Together, they contribute to the operations of the Level-1 Trigger and High Level Trigger studies. Prof. Bose has a leadership position within US CMS as the Deputy Software & Computing Project Manager and is actively engaged in energizing US CMS R&D efforts for developing the computing and software systems for the HL-LHC.

Project: CC* Compute: GPU Augmented Computing Resources for Wisconsin Physics & Beyond (with Dasu)
Source: NSF
Total Award: $ 400,000 Period: 04/01/20-03/31/22
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.09 Sumr: 0.00
Abstract: This proposal covers the creation of a new computational cluster at the University of Wisconsin-Madison Physics Department that will support computationally intensive research projects in physics and also other disciplines both on campus and beyond. The cluster will comprise graphical processing units (GPUs) and provide state-of-the-art high-performance computing resources to support research activities both locally at the university via the Center for High Throughput Computing and also nationally via the Open Science Grid. Some of the projects supported will enable discoveries in areas such as particle physics, astro-particle physics, cosmology, computational biology and beyond as well as enable development of machine learning algorithms for a wide range of research areas. The proposed cluster will provide resources to the Open Science Grid and will benefit the broader science community by enabling researchers across US universities and laboratories. The cluster is also planned to be used for education and outreach and will support new student learning opportunities through undergraduate and graduate research that focus on high-performance computing.

Current and Pending Support
SRIDHARA DASU
1/21/20

Current:

Project: High Energy Physics Research: CMS @ LHC (with Smith and Herndon)
Source: DOE DE-SC0017647
Total Award: $ 3,625,000 Period: 04/01/17-03/31/20
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00
Abstract: The CMS (Task T) activity of Profs. Sridhara Dasu, Matt Herndon and Wesley Smith continues leadership roles in characterization of the Higgs Boson, searches for its potential partners, searches for Dark Matter and extensive studies of Electroweak phenomena. The UW group built, upgraded, commissioned and operates, major parts of CMS: the trigger system, including the Level-1 (L1) calorimeter trigger and higher level triggers (HLT), the endcap muon system (EMU), including its chambers, infrastructure, software for simulation and event processing, and a leading Tier-2 computing facility. The UW group proposes to actively update and improve these systems to harvest new physics results from the challenging opportunity of increasing LHC luminosity. The UW group also has active leadership roles in the CMS HL-LHC upgrades for these systems and proposes to develop their next generation with demonstrated capabilities to maximally extend the physics reach of CMS over the coming decade.

Project: US CMS Operations at the LHC
Source: Princeton (NSF) SUB0000186
Total Award: $ 1,469,135 Period: 01/01/17-12/31/21
Location: UW Madison, CERN
Abstract: This project funds support for US CMS Tier 2 computing, EMU operations, and Trigger operations. Synergy with the base grant.

Project: US CMS Trigger Operations
Source: Fermilab 657695
Total Award: $ 267,189 Period: 06/14/19-03/31/20
Location: UW Madison, CERN
Abstract: This project funds support for US CMS Trigger maintenance and operations. Synergy with the base grant.

Project: US CMS High Level Trigger Upgrade
Source: Fermilab 657680
Total Award: $ 268,941 Period: 06/14/19-05/31/20
Location: UW Madison, CERN
Abstract: This project funds support for US CMS HL Trigger upgrade at CERN. Synergy with the base grant.

Current and Pending Support
SRIDHARA DASU
1/21/20

Project: US CMS Detector Support
Source: Fermilab 655785
Total Award: $ 78,935 Period: 04/17/19-04/30/20
Location: UW Madison, CERN
Abstract: This project funds support for US CMS Detector Support at CERN. Synergy with the base grant.

Project: US CMS EMU Support
Source: Fermilab 656922
Total Award: $ 97,687 Period: 05/24/19-05/31/20
Location: UW Madison, CERN
Abstract: This project funds support for US CMS EMU at CERN. Synergy with the base grant.

Project: HL Trigger Upgrade
Source: Wisconsin Alumni Research Foundation
Total Award: $ 46,748 Period: 07/01/18-06/30/20
Location: UW Madison, CERN
Abstract: This project funds support for the Trigger Upgrade at CERN. Synergy with the base grant.

Pending

Project: High Energy Physics Research: CMS @ LHC (with Black, Bose, Herndon)
Source: DOE (this proposal)
Total Award: $ 4,296,445 Period: 04/01/20-03/31/23
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00
Abstract: Renewal of the above.

Project: CC* Compute: GPU Augmented Computing Resources for Wisconsin Physics & Beyond (PI: Bose)
Source: NSF
Total Award: $ 400,000 Period: 04/01/20-03/31/22
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.09 Sumr: 0.00
Abstract: This proposal covers the creation of a new computational cluster at the University of Wisconsin-Madison Physics Department that will support computationally

intensive research projects in physics and also other disciplines both on campus and beyond. The cluster will comprise graphical processing units (GPUs) and provide state-of-the-art high-performance computing resources to support research activities both locally at the university via the Center for High Throughput Computing and also nationally via the Open Science Grid. Some of the projects supported will enable discoveries in areas such as particle physics, astro-particle physics, cosmology, computational biology and beyond as well as enable development of machine learning algorithms for a wide range of research areas. The proposed cluster will provide resources to the Open Science Grid and will benefit the broader science community by enabling researchers across US universities and laboratories. The cluster is also planned to be used for education and outreach and will support new student learning opportunities through undergraduate and graduate research that focus on high-performance computing.

Current and Pending Support
MATTHEW F. HERNDON
1/20/20

Current:

Project: High Energy Physics Research: CMS @ LHC (with Smith and Dasu)
Source: DOE DE-SC0017647
Total Award: $ 3,625,000 Period: 04/01/17-03/31/20
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00
Abstract: The CMS (Task T) activity of Profs. Sridhara Dasu, Matt Herndon and Wesley Smith continues leadership roles in characterization of the Higgs Boson, searches for its potential partners, searches for Dark Matter and extensive studies of Electroweak phenomena. The UW group built, upgraded, commissioned and operates, major parts of CMS: the trigger system, including the Level-1 (L1) calorimeter trigger and higher level triggers (HLT), the endcap muon system (EMU), including its chambers, infrastructure, software for simulation and event processing, and a leading Tier-2 computing facility. The UW group proposes to actively update and improve these systems to harvest new physics results from the challenging opportunity of increasing LHC luminosity. The UW group also has active leadership roles in the CMS HL-LHC upgrades for these systems and proposes to develop their next generation with demonstrated capabilities to maximally extend the physics reach of CMS over the coming decade.

Pending

Project: High Energy Physics Research: CMS @ LHC (with Black, Bose, Dasu)
Source: DOE (this proposal)
Total Award: $ 4,296,445 Period: 04/01/20-03/31/23
Location: UW Madison, CERN
Commitment to Project: Cal: 0.00 Acad: 0.00 Sumr: 2.00
Abstract: Renewal of the above.

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. Internal note numbers are also cited. The group members have presented 21 CMS and 3 ATLAS talks, as well as 4 posters, at conferences, based on these physics results in 2017, 2018 and 2019. Over 3000 internal CMS talks on operations, upgrades and physics analysis details were also given.

1. *Public Paper*: "*The CMS experiment at the CERN LHC"*, JINST 0803, S08004 (2008). Internal documents: Based on multiple documents. UW contribution to EMU/Trigger/Tier-2.
2. *Public Paper*: Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys.Lett. B716 (2012) 30-61.
   Internal Notes: Based on multiple documents. UW contribution in ττ and ZZ* modes.
3. *Public Paper*: Observation of a new boson with a mass near 125 GeV in pp collisions at $\sqrt{s}$ = 7 and 8 TeV, *J. of High Energy Phys*, 81 (2013), arXiv:1303.4571.
   Internal Notes: Based on multiple documents. UW contribution in ττ and ZZ* modes.
4. *Public Paper*: Measurement of the WZ production cross section in pp collisions at sqrt(s) = 13 TeV, Phys. Lett. B 766 (2017) 268.
   Internal Note: D. Taylor, K. Long, N. Smith, N. Woods, S. Duric, S. Savin, M. Herndon and S. Dasu. Measurement of the WZ production cross section in lvll decays in pp collisions at sqrt(s) = 13 TeV, AN-2016/028.
5. *Public Paper*: Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at sqrt(s) = 13 TeV, Phys. Lett. B 795 (2019) 281. Internal Note: CMS AN-2017/135, K. Long, N. Smith, M. Herndon, S. Duric, A. Savin.
6. *Public Report*: "Les Houches 2017: Physics at TeV Colliders Standard Model Working Group Report," FERMILAB-CONF-18-122-CD-T, UWTHPH-2018-5, K Long
7. *Public Report*: *"Vector boson scattering: Recent experimental and theory developments,"* Rev. Phys. 3 (2018) 44-63, K Long, M. Herndon
8. *Public Paper*: Measurements of the pp→ZZ production cross section and the Z→4ℓ branching fraction, and constraints on anomalous triple gauge couplings at s√= 13 TeV, Eur. Phys. J. C 78 (2018) 165, Erratum: Eur. Phys. J. C 78 (2018) 515. Internal Note: CMS AN-2016/359 N. Woods, K. Long, W. Smith, M. Herndon, S. Duric, A. Savin.
9. *Public Paper*: Measurement of differential cross sections for Z boson pair production in association with jets at sqrt(s) = 8 and 13 TeV, Phys. Lett. B 789 (2019) 19. Internal Note: CMS AN-2014/135, N. Woods, W. Smith, S. Dasu, A. Savin.
10. *Public Physics Analysis Summary*: Measurement of the pp→ZZ production cross section at s√= 13 TeV with the Run 2 data set, CMS-PAS-SMP-19-001. Internal Notes: CMS AN-2019/004, CMS AN-2019/191, U. Hussain, S. Dasu, M. Herndon, K. Long, S. Savin.
11. *Internal Note*: Measurement of the pp→ZZ production cross sections and aTGC at s= 13 with the full sample of Run 2 data. Paper in preparation CMS-19-001, Internal Note: CMS AN 2019/191, U Hussain, K. Long, B. Gomber, S. Duric, A. Savin, S. Dasu, M. Herndon.
12. *Public Paper*: Measurement of electroweak production of a W boson in association with two jets in proton-proton collisions at sqrt(s) = 13 TeV, Submitted to EPJC March 2019. Internal Note: CMS AN-2017/161. S. Duric.
13. *Public Paper*: Electroweak production of two jets in association with a Z boson in proton-proton collisions at s√= 13 TeV, Eur. Phys. J. C 78 (2018) 589. Internal Note: CMS AN-2016/379, S. Duric.
14. *Public Paper*: Search for W boson decays to three charged pions, Phys. Rev. Lett. 122, 151802 (2019). Internal Note: CMS AN-2018/135, C. Caillol, S. Dasu.
15. *Public Physics Analysis Summary*: Measurement of the production cross section for pp → Zγ → ννγ at sqrt(s) = 13 TeV at CMS, CMS PAS SMP-16-004.
    Internal note: Perry, Buchanan, Dasu, Gomber and Smith, AN-2016/051.

16. *Internal Note*: Measurement of the Z(νν) + γ cross section in monophoton event at 13 TeV using 2016 data. Internal Note: CMS AN-2018/178, J. Buchanan, B. Gomber, S. Dasu.
17. *Public Physics Analysis Summary*: Prospects for the measurement of electroweak and polarized WZ→3l ν production cross sections at the High-Luminosity LHC, CMS-PAS-FTR-18-038. Internal Note: CMS AN-2018/220, D. Teague, K. Long, M. Herndon, A. Savin.
18. *Public Paper*: Combined measurements of Higgs boson couplings in proton-proton collisions at sqrt(s) = 13 TeV, Eur. Phys. J. C 79 (2019) 421. Internal Notes: Based on multiple documents. UW contribution in τ pair and ZZ* modes.
19. *Public Paper:* Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at √s =13 TeV, JHEP *127 (2018)*. *Internal Note*: S. Duric, K. Long, A. Savin and N. Wood, AN-2017/019.
20. *Public Paper*: Search for neutral Higgs bosons decaying to tau pairs in pp collisions at √s=7 TeV, *Phys. Lett. B* 713 (2012) 68-90. Internal Note: M. Bachtis, J. Swanson, E. Friis, A. Savin, S. Dasu, CMS AN-2011/390.
21. *Public Paper*: Evidence for the 125 GeV Higgs boson decaying to a pair of tau leptons, JHEP 05 (2014) 104. *Internal Note*: J. Swanson, I. Ojalvo, A. Savin, S. Dasu, W. Smith, CMS AN-2013/178.
22. *Public Paper:* Observation of the Higgs boson decay to a pair of tau leptons with the CMS detector, Phys. Lett. B 779 (2018) 283, Internal Note: AN-2016/355, L. Dodd, T. Ruggles, S. Dasu, C. Caillol, I. Ojalvo, A. Savin.
23. *Internal Note:* Measurement of Higgs Boson production and decay to a pair of tau leptons using the full Run 2 dataset. CMS AN-19-109, A. Loeliger, C. Caillol, J. Madhusudanan, A. Mallampalli, T. Bose, S. Dasu
24. *Public Paper*: Measurement of the Z γ *→ τ τ cross section in pp collisions at sqrt (s)= 13 TeV and validation of τ lepton analysis techniques, Eur. Phys. J. C 78 (2018) 708. Internal Note: CMS AN-2016/027, L. Dodd, T. Ruggles, S. Dasu.
25. *Public Paper*: Search for the associated production of the Higgs boson and a vector boson in proton-proton collisions at s√= 13 TeV via Higgs boson decays to τ leptons, JHEP 06 (2019) 093. Internal Note: CMS AN-2017/020, T. Ruggles, A. Loeliger, J. Madhusadanan, C. Caillol, B. Gomber, S. Dasu, A. Savin.
26. *Public Paper*: Constraints on anomalous HVV couplings from the production of Higgs bosons decaying to τ lepton pairs, Phys. Rev. D 100, 112002 (2019). Internal Note: CMS AN-2016/355, CMS AN-2017/212, L. Dodd, T. Ruggles, I. Ojalvo, S. Dasu, S. Duric, C. Caillol, A. Savin.
27. *Public Physics Analysis* Summary: Search for a neutral MSSM Higgs boson decaying into tautau at 13 TeV, CMS PAS HIG-16-006. *Internal Note*: L Dodd, I Ojalvo, T Ruggles. CMS AN-2016/045.
28. *Public Paper*: Search for a heavy pseudoscalar Higgs boson decaying into a 125 GeV Higgs boson and a Z boson in final states with two tau and two light leptons at sqrt(s) = 13 TeV, Submitted to JHEP. Internal Note: CMS AN-2017/276, T. Ruggles, S. Dasu.
29. *Public Paper*: Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two τ leptons in proton-proton collisions at s√= 13 TeV, Phys. Lett. B 785 (2018) 462. Internal Note: CMS AN-2017/172, C. Caillol, S. Dasu.
30. *Public Paper*: Search for lepton-flavour-violating decays of the Higgs boson, Phys. Lett. B 749 (2015) 337. *Internal Note*: A. Levine, E. Friis, M. Cepeda, S. Dasu, CMS AN-2013/244.
31. *Public Paper*: Search for lepton flavour violating decays of the Higgs boson to e tau and e mu in proton-proton collisions at sqrt(s)=8 TeV, Submitted to Phys. Lett. B. *Internal Note*: CMS AN-2014/231 A. Levine, E. Friis, M. Cepeda, S. Dasu.

32. *Public Physics Analysis Summary*: Search for Lepton Flavour Violating Decays of the Higgs Boson in the mu-tau final state at 13 TeV, CMS PAS HIG-16-005. *Internal Note*: CMS AN-2016/024, A. Levine, M. Cepeda, S. Dasu.
33. *Public Paper:* Search for lepton flavour violating decays of the Higgs boson to $\mu\ \tau$ and e τ in proton-proton collisions at sqrt(s) = 13 TeV , JHEP 06 (2018) 001. Internal Note: CMS AN-2016/441, A. Levine, M. Cepeda, C. Caillol, S. Dasu.
34. *Public Physics Analysis Summary:* Search for invisible Higgs bosons in pp→ZH→2ℓ+EmissT channels at s√=13 TeV, CMS PAS HIG-16-008. *Internal Note*: AN-2015/322, N. Smith, B. Gomber, S. Dasu, CMS.
35. *Public Physics Analysis Summary*: A combination of searches for invisible Higgs boson decays using run I and run II data samples, CMS PAS HIG-16-016. N. Smith, B. Gomber, S. Dasu.
36. *Public Paper*: Performance of reconstruction and identification of τ leptons decaying into hadrons and υ_τ at $\sqrt{s}$ = 13 TeV, JINST 13 (2018) P10005, CMS-AN-2016/375 C. Galloni
37. *Public Paper:* Search for narrow high-mass resonances in proton-proton collisions at 8 TeV decaying to a Z and a Higgs Boson, CMS-AN-2016/377, CMS-AN-2016/376 Physics Letters B, 748 (2015) 255-277, C. Galloni
38. *Public Paper:* Search for heavy resonances decaying into two Higgs Bosons or into a Higgs boson and a W or Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS-AN-2016/275, JHEP (2019) 51) , C. Galloni
39. *Public Physics Analysis Summary*: Search for Dark Matter and Large Extra Dimensions in the gamma + MET final state in pp Collisions at sqrt(s) = 13 TeV, CMS PAS EXO-16-014. *Internal Note*: CMS AN-2016/050, T. Perry, J. Buchanan, B. Gomber, S. Dasu.
40. *Public Physics Analysis Summary*: Search for dark matter and graviton produced in association with a photon in pp collisions at sqrts = 13 TeV, CMS PAS EXO-16-039. *Internal Note*: CMS AN-2016/224, T. Perry, J. Buchanan, B. Gomber, S. Dasu.
41. *Public Paper*: Search for new physics in final states with a single photon and missing transverse momentum in proton-proton collisions at sqrt(s)=13 TeV. JHEP 02 (2019) 074. *Internal Note*: CMS AN-2016/475, J. Buchanan, B. Gomber, S. Dasu.
42. *Public Paper*: Search for dark matter particles produced in association with a Higgs boson in proton-proton collisions at sqrt(s)= 13 TeV, Submitted to JHEP. *Internal Note*: CMS AN-2018/102, L. Dodd, B. Gomber, S. Dasu.
43. *Public Paper*: Search for dark matter produced in association with a Higgs boson decaying to $\gamma\ \gamma$ or $\tau+\tau-$ at s√= 13 TeV, JHEP 09 (2018) 046. Internal Note: CMS AN-2016/393, L. Dodd, S. Dasu, B. Gomber.
44. *Public Paper*: Search for dark matter and unparticles in events with a Z boson and missing transverse momentum in pp collisions at sqrt(s) = 13 TeV, JHEP 03 (2017) 061. *Internal Note*: CMS AN-2015/285, N.Smith, B. Gomber, S. Dasu.
45. *Public Physics Analysis Summary*: Search for dark matter in Z + E_T^miss events using 12.9 fb-1 of 2016 data, CMS PAS EXO-16-038. *Internal Note*: CMS AN-2016/199, N.Smith, B. Gomber, S. Dasu.
46. *Public Paper:* Search for new physics in events with a leptonically decaying Z boson and a large transverse momentum imbalance in proton-proton collisions at sqrt(s) = 13 TeV, Eur. Phys. J. C 78 (2018) 291. *Internal Note*: AN-2016/465, N.Smith, B. Gomber, S. Dasu.
47. *Public Paper*: Search for dark matter produced in association with heavy quarks in proton-proton collisions at sqrt(s) = 13 TeV, Eur. Phys. J. C 77 (2017) 845. *Internal Note*: CMS AN-2015/099, D. Pinna.
48. *Public Paper*: Search for dark matter particles produced in association with a top quark pair at sqrt(s) = 13 TeV, Phys. Rev. Lett. 122, no. 1, 011803 (2019), *Internal Note*: CMS AN-2016/417, D. Pinna.

49. *Public Paper*: Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at sqrt(s) = 13 TeV, JHEP 03 (2019) 141. *Internal Note*: CMS AN-2017/327, D. Pinna, T. Bose.
50. *Public Paper*: Search for top-quark partners with charge 5/3 in the same-sign dilepton final state, Phys. Rev. Lett. 112, 171801 (2014), *Internal Note*: CMS AN-2012/491, A. Avestiyan, C. Richardson, T. Bose.
51. *Public Paper*: Search for top quark partners with charge 5/3 in proton-proton collisions at 13 TeV, JHEP 1708 (2017) 73, *Internal Note*: CMS AN-2016/210, CMS-2015/148, C. Richardson, A. Avetisyan, T. Bose.
52. *Public Paper*: Search for top quark partners with charge 5/3 in same-sign dilepton and single-lepon final states in proton-proton collisions at 13 TeV, JHEP 03 (2019) 082, *Internal Note*: CMS AN-2017/138, C. Richardson, T. Bose.
53. *Public Paper*: Review of Particle Physics, Phys. Rev. D, 98 (2018) 030001, K. Black
54. *Public Paper*: Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisons at 8 TeV with the ATLAS detector", JHEP 11 (2014) 104
55. *Public Paper*: Search for a W' boson decaying to a bottom quark and a top quark in pp collisions at 7 TeV, Phys. Lett. B 718 (2013) 1229, *Internal Note*: CMS AN-2011/404, CMS AN-2012/049, D. Sperka, T. Bose.
56. *Public Paper*: Search for W' to t b decays in the lepton+jets final state in pp collisions at 8 TeV, JHEP 05 (2014) 108, *Internal Note*: CMS AN-2012/493, D. Sperka, T. Bose.
57. *Public Paper*: Searches for the W' boson decaying into a top and a bottom quark in the lepton+jets final state in proton-proton collisions at 13 TeV, Phys. Lett. B 777 (2018) 39, *Internal Note*: CMS AN-2016/418, D. Rankin, T Bose
58. *Public Paper*: Searches for W' bosons decaying to a top quark and a bottom quark in proton-proton collisions at 13 TeV, JHEP 08 (2017) 029, *Internal Note*: CMS AN-2016/315, D. Rankin, T. Bose.
59. *Public Paper*: Measurement of the production of a top quark in association with a Z boson in prton-proton collisions at 13 TeV, Phys. Lett. B 780 (2018) 557 : L. Dell'Astta, A. Sherman, K. Black
60. *Public Paper*: Measurements of normalized differential cross-section for tt production in pp collisions at 7 TeV with the ATTLAS detector, Phys. Rev. D 90, 072004: C. Bernard, K. Black
61. *Public Paper*: Measurement of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at 8 TeV using the ATLAS detector, Eur. Phys. J. C76 (2016) 538.
62. The Babar Collaboration, Evidence of an excess of B-> D* tau nu decays, PRL vol 101802, 2012
63. The Babar Collaboration, Measurement of an excess of B -> D* tau nu decays and implications for charged higgs bosons," Physical Review D, vol. 92, no. 072012, 2013.
64. The Belle Collaboration, "Measurement of the Branching ratio of B -> D* tau nu relative to B -> D* l nu decays with hadronic tagging at Belle," Physical Review D, vol. 072014, 2015.
65. The Belle Collaboration, "Measurement of the branching ratio of B-> D* tau nu relative to B -> D* l nu decays with a semileptonic tagging method," Physical Review, vol. 072007, 2016.
66. The LHCB Collaboration, "Test of the Lepton Flavor Universality by the measurement of the B ->D tau nu branching fraction using three-prong tau decays," Physical Review D, vol. 97, no. 7, 2018.
67. The HFLAV Collaboration, "Averages of b-hadron, c-hadron, and tau-lepton properties as of summer 2016," European Physics Journal C, vol. 77, no. 12, p. 895, 2017.
68. The LHCB Collaboration, "Test of Lepton Universality using B-> K ll decays," Physics Review Letters, vol. 113, no. 151601, 2014.
69. The LHCb Collaboration, "Tests of Lepton Universality with B-> K ll Decays," Journal of High Energy Physics, vol. 55, 2017.
70. Z. L. a. J. R. M. Freytsis, "Flavor Models for B -> D tau nu," Physical Review D, no. 054018, 2015.
71. Public Paper: Particle-flow reconstruction and identification of tau leptons with the CMS detector, JINST, vol 13, no 10, p 10003, 2017: C. Galloni
72. Public Paper: Technical Design Report for the Phase-II Upgrade, CERN-LHCC-020: K. Black

73. *Public Physics Analysis Summary*: Measurements of properties of the Higgs boson and search for an additional resonance in the four-lepton final state at sqrt(s) = 13 TeV, CMS PAS HIG-16-033.
    Internal Note: K. Long, N. Smith, A. Savin, CMS AN-2016/217.
74. *Public Physics Analysis Summary*: Search for Dark Matter and Large Extra Dimensions in the gamma + MET final state in pp Collisions at sqrt(s) = 13 TeV, CMS PAS EXO-16-014.
    Internal Note: T. Perry, J. Buchanan, B. Gomber, S. Dasu, CMS AN-2016/050.
75. *Public Physics Analysis Summary*: Search for dark matter and graviton produced in association with a photon in pp collisions at sqrts = 13 TeV, CMS PAS EXO-16-039.
    Internal Note: T. Perry, J. Buchanan, B. Gomber, S. Dasu, CMS AN-2016/224.

Laboratory & Major Equipment:
The CMS group has 1865 square feet of laboratory space used as an electronics testing and development facility in the Physics Building at UW Madison. This facility has a 12 GHz, 40 GSa/s Agilent Digital Signal Analyzer and 4 channel 20 GSa/s 4 GHz Agilent Oscilloscope. There are also optical scopes for board inspection, chip replacement re-soldering equipment, μTCA test crates, water-cooled racks and computers with dedicated interfaces for testing.

There is sufficient space for parallel production testing used in the past for two 20 9U-VME crate trigger systems with large numbers of associated cards (ZEUS and CMS original calorimeter triggers) plus the μTCA Phase-1 upgrade calorimeter trigger with more than 3,000 cards tested over the past 25 years.

The CMS lab at Wisconsin has a test system with a full crate of 12 μTCA Phase-1 upgrade calorimeter trigger cards, the CTP7 with a Virtex-7 FPGA as its primary data processor, the ZYNQ System-on-Chip running embedded Linux to provide TCP/IP communication and board support functions and multi-gigabit (up to 10 Gb/s) input/output on optical fibers are located on the front side of the CTP7 and connected to a custom μTCA backplane. This setup is used in support of the UW HL-LHC Calorimeter and Correlator Trigger upgrades and a number of CMS R&D programs that have adopted CTP7-based development hardware systems at CERN and Cornell for the HL-LHC L1 tracking trigger, CERN for EB HL-LHC readout R&D with Notre Dame, Rutgers and U. Virginia and both CERN and Texas A&M for EMU HL-LHC R&D and by the CMS GEM collaboration for their GE1/1 μTCA-based backend processing board.

The ATLAS and LZ experimental groups currently have no need of lab space on the Wisconsin campus as lab activities take place off-site. Should the need for lab space in the Wisconsin physics building become necessary, suitable space will be made available to the groups.

Computing:
The CMS Tier-2 Computing center at UW-Madison operates ~500 computer nodes with about ~8800 job slots providing ~85500 HS06 units of processing power (~190,000 hours of computing per day), and ~4950 TB of raw storage, purchased using NSF support. These resources are fully integrated with Open Science Grid and the Wisconsin campus grid, which began as the GLOW project. These UW resources operate as part of World-wide LHC Computing Grid to serve needs of the CMS experiment for central organized data processing, and also serve the UW, US CMS and their collaborators. The water-cooled rack space, power and networking equipment are provided by the UW-Madison.

At present, the Wisconsin-ATLAS Computing cluster operates about ~1200 cores and ~700 TB of raw storage, purchased using the Wisconsin University funding. Also, the Wisconsin-ATLAS group provides strong support for producing the MxAOD data for ATLAS physics working groups. The rack space, cooling system, power and networking equipment and manpower for maintenance are provided by Wisconsin Physics Department and Computer Sciences Department.

The Department provides additional research computing support through its personnel, who provide all groups with AFS space, linux cluster access with physics and mathematics software, and backups. When massive computational resources are needed, the HEP group (ATLAS, CMS, LZ, DES, VRO/LSST, and Theory groups) uses Wisconsin Center for High-Throughput Computing, http://chtc.cs.wisc.edu, which provides about a million hours of computing per day.

The UW is connected to the wide-area network with high bandwidth lines enabling seamless access to the worldwide computing grid. This is especially important for our close collaboration with Fermi and Brookhaven National Laboratories (connected at 100 Gb/s), and to the ATLAS and CMS Tier-0 sites at CERN.

Office:
The PI, Co-PIs, staff, and students have office space in the Physics Building.

Other:
The Physics Department has seminar rooms and a large library. The Department provides grant administrative support, travel support personnel, and purchasing personnel to assist the HEP group as needed.

There is a vibrant mix of theoretical and experimental faculty in theoretical nuclear physics, particle physics, and astrophysics at Wisconsin. Interactions among Co-PIs on this proposal and with other local colleagues will enhance the research proposed here.

Other Resources:
ATLAS has US ATLAS resources provided by Brookhaven National Lab to support engineering and technical personnel. Software engineers Haimo Zobernig and Werner Wiedenmann work on Trigger/DAQ, High Level Trigger (HLT) and upgrades. In 2014, Werner Wiedenmann was awarded the "ATLAS Outstanding Achievement Award" for his contributions to ATLAS Trigger/DAQ, HLT and core software. He coordinates the trigger core software group, works on the HLT Event Selection framework and maintains HLT integration tools, simulation code and monitoring software. He also provides software support for TDAQ testing and HLT processor evaluation. Haimo Zobernig worked until May 2019 full-time on adapting and maintaining tools for automated non-interactive execution of Trigger/DAQ and HLT partitions. He maintained a configuration package for the generation of partitions from small test setups to full ATLAS configurations. Both have worked with graduate students in the trigger area.

The longstanding success of the collaboration with Torre Wenaus of BNL recently led the US ATLAS HL-LHC Computing management to involve the Wisconsin group in an expanded HL-LHC computing R&D effort, in particular, on ATLAS machine learning infrastructure. US ATLAS provides part time support for Wisconsin postdoc Rui Zhang contributing to that program.

For ATLAS, Torre Wenaus of BNL arranged to support Wen Guan part time through the Computer Sciences Department at the University of Wisconsin, to promote part of Wen's work on Event Streaming Service.

US ATLAS resources provided by Brookhaven National Lab also support engineer John Joseph to work on the ATLAS silicon detector. He maintains and modifies the firmware used by the

FPGA devices on the silicon readout drivers. He implements new features and functions that improve the performance of the device. John Joseph is also responsible for storing hardware replacement parts and for providing diagnostics and board rework tools.

For ATLAS, the prior UW Chancellor, through the Vilas Foundation, awarded the Wisconsin-ATLAS group $1 million for a Tier 3 center to be used and upgraded throughout a number of years. This has enabled us to analyze data efficiently and to set our own priorities, which has contributed greatly to our success in the Higgs discovery.

CMS has US CMS Project (both DOE and NSF) supported engineering and technical personnel. Electronics Engineer Tom Gorski was responsible for the engineering for final construction, commissioning and operation of the original CMS Regional Calorimeter Trigger and its phase-1 upgrade, and development of its HL-LHC upgrade. Firmware Engineers Ales Svetek and Marcelo Vicente (based at CERN) are responsible for firmware for the Phase-1 Layer-1 Calorimeter Trigger system and engineering and firmware development for its HL-LHC upgrade. Software engineer Jesra Tikalsky is author of software adopted by CMS for use with μTCA systems, software for the Phase-1 Layer-1 Calorimeter Trigger system and software development for its HL-LHC upgrade. Technician Bob Fobes has worked on the layout, production, assembly of the CMS and ZEUS trigger electronics. This UW engineering team also provides support for the CMS R&D programs that have adopted the CTP7-based development hardware systems detailed above.

The US CMS Tier-2 program supports software and computing experts Ajit Mohapatra and Carl Vuosalo, who assist and enable running of analysis jobs and the computing infrastructure.

The Department of Physics provides about 0.5 FTE to the HEP group through the invaluable services of the Director of Computing Mr. Dan Bradley and Systems Programmer Dr. Chad Seys. They are both experts in high-throughput computing and work closely to support the large scale computing installations of ATLAS and CMS experiments, in addition to providing access to HT-Condor based grid computing pioneered by the Department of Computer Science researchers. We maintain a strong collaboration with Prof. Miron Livny (Director of CHTC and OSG PI) and his group, who are originators of much of the GRID middleware used today in scientific computing.

This proposal also contains US CMS Project partially supported physicist labor of 1 Senior Scientist. Senior Scientist Armando Lanaro (75% project funds/25% base grant), based at CERN, is the CMS CSC Project Manager, the US CMS Level-3 Manager in charge of Endcap Muon System Integration and was the CMS Manager of the EMU Chamber factory for the recently completed upgrade, providing 72 new chambers.

Emeritus Distinguished Scientist Dr. Richard Loveless was the US CMS EMU Operations Manager, CMS EMU Technical Coordinator and CMS EMU upgrade project manager and is available for consultations as needed.

The US CMS Project supports engineering and technical personnel for Engineers T. Gorski, Ales Svetek and Technicians R. Fobes and C. Farrow. Mr. Gorski's knowledge of and expertise in the trigger system is essential to its successful operation. He also leads the engineering effort on our HL-LHC upgrade trigger program. Mr. Svetek is responsible for the growing library of calorimeter trigger firmware for the present trigger and upgrade studies. Mr. Fobes has a significant amount of technical work required at UW for CMS in the next few years, including repair of printed circuit boards with surface mount devices, general repair of electronic components, cabling, inventory of parts and maintaining supply cabinets, parts ordering and maintenance and repair of test setups. CERN-resident technician Farrow works on the Trigger and Muon electronics and detectors (e.g. chamber construction and testing) as well as with CMS Technical Coordination and provides mechanical and electronics technical work for the HCAL ECAL, and BRIL (Beam Radiation Instrumentation and Luminosity project on the Pixel Luminosity Telescope) projects as determined by US CMS Research Program Management. Engineer Svetek also assists in the HCAL upgrade project as requested by US CMS Management.

Facilities at Fermi National Accelerator Laboratory are available for NOvA collaborators and for the DUNE project, spanning office space for the postdocs, and computing resources.

The University of Wisconsin's Physical Sciences Laboratory (PSL) (see below) will be a primary manufacturing facility for the DUNE anode plane assemblies (APA). There are several mechanical and electrical engineers and technicians at this facility, as well as a machine shop. These resources will be critical to the success of the proposed efforts to study the ProtoDUNE APA performance and develop quality controls for the DUNE APAs.

The group has the necessary lab space at the University of Wisconsin to develop quality assurance and quality control tests for the DUNE APA production before deployment at the PSL.

Rebel used start-up funds to develop a remote control room for use initially with NOvA and then DUNE. This control room allows the Rebel and Thomas group to fulll their shift requirements for experiments without the need for additional travel resources.

Facilities at SLAC National Accelerator Laboratory are available for the LZ project, spanning office space for visiting scientists, machine shops and technician support, and the cryogenic liquid noble test facility in the IR-2 (old BaBar) hall. LZ Collaborators are SLAC users and also have access to SLAC computing accounts and resources.

Another important resource for experimental groups at Wisconsin is the **Physical Sciences Laboratory** (PSL). From small equipment and research tools to large projects in need of complex design and fabrication, PSL provides consulting, engineering, fabrication, and calibration services for both public institutions and private businesses worldwide. PSL has a highly trained staff of electrical engineers, mechanical engineers, machinists, and physicists and extensive mechanical and electronics shops and assembly areas available on an as needed basis for projects. PSL was responsible for such projects as the endcap steel disks for CMS and their associated infrastructure, engineering for Daya Bay, ice-drilling and module installation for IceCube, and the Steel Yoke for ZEUS. PSL has played an important role to date in LZ and PSL Engineer Jeff Cherwinka is the US lead LZ engineer.

As it has since 1993, PSL Engineering and technical work will continue to support the CMS project where PSL was responsible for the construction of the CMS endcap disks, the installation and infrastructure of its chambers and involved in the beampipe shielding. Modifications and movements of these structures typically involve PSL. The PSL group has been contracted by international CMS to provide engineering solutions for CMS, such as in the recent successful repair and retrofit for water leaks on Russian-built CSC chambers in the CMS endcap. The planned HL-LHC upgrade work on the CMS endcap disks for the new endcap calorimeter and the upgrade of the CSC on-chamber electronics (requiring chamber removal) will involve PSL. Therefore, the Wisconsin-CMS group has been invited by the CMS management to continue to provide mechanical engineering support for its HL-LHC projects.

More information about PSL is available at: http://www.psl.wisc.edu

Equipment

UW has a dedicated electronics repair, development and testing lab for CMS at CERN (supported by the US CMS Research program) at the Prevessin site with 2 crates with the μTCA Phase-1 upgrade calorimeter trigger cards, the CTP7 with a Virtex-7 FPGA as its primary data processor, the ZYNQ System-on-Chip running embedded Linux to provide TCP/IP communication and board support functions and multi-gigabit (up to 10 Gb/s) input/output on optical fibers located on the front side of the CTP7 and connected to a custom μTCA backplane. The laboratory also has high speed oscilloscope and logic analyzer as well as electronics repair equipment. This setup is used in support of the UW built, installed and operational Phase-1 upgrade Layer-1 calorimeter trigger system, the UW HL-LHC Calorimeter and Correlator Trigger upgrades and a number of US CMS R&D programs that have adopted CTP7-based development hardware systems at CERN for the HL-LHC L1 tracking trigger in collaboration with Cornell, the EB HL-LHC readout R&D with Notre Dame, Rutgers and U. Virginia and EMU HL-LHC R&D with Texas A&M and the CMS GEM collaboration for their GE1/1 μTCA-based backend processing board.

Data Management Plan – Energy Frontier Groups at Wisconsin (CMS & ATLAS)

ATLAS
Our proposed research work is in collaboration with the ATLAS Collaboration. Therefore, our Data Management Plan (DMP) is the same as that of the ATLAS Collaboration: ATLAS Data Access Policy Document: ATLAS-CB-PUB-2015-001 (2015)
https://po.usatlas.bnl.gov/programoffice/datamanagementpolicy.php

CMS
Our proposed research work is in collaboration with the CMS Collaboration. Therefore, our Data Management Plan (DMP) is the same as that of the CMS Collaboration: CMS Data Policy Document: CMS Document 6032-v1.2 (2018)
https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=6032