TASK T: CMS at the LHC

1 Overview

The UW group of Profs Sridhara Dasu, Matt Herndon and Wesley Smith proposes to continue its active leadership roles in the Compact Muon Solenoid (CMS) experiment [1] at the LHC, as we explore proton-proton collisions at 13 TeV and prepare for future higher luminosity running. The UW group is leading physics analyses in characterization of the Higgs Boson [2,3], searches for its potential partners, searches for particle dark matter, and extensive studies of Electroweak phenomena. 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 and new cathode strip chambers (CSCs), 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.

2 Physics Analysis Activity

2.1 Overview

2.1.1 Current Research

Our primary physics activities are the study of electroweak symmetry breaking mechanism, searches for associated new physics phenomena and searches for the source of particle dark matter. 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 contributions to the Higgs discovery decay mode into four leptons and preliminary evidence of Higgs coupling to fermions via τ-lepton pairs. Our electroweak physics analysis effort has resulted in papers on vector boson with heavy flavor production, di-boson production and searches for anomalous triple 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, Senior Scientist Savin and Postdoc Duric focus on supervision of the SM measurements and associated new physics phenomena. Profs. Dasu and Smith, with their Postdocs Caillol and Gomber, focus on SM higgs characterization, while searching for new physics in both higgs and dark matter sectors. Scientists Klabbers and Lanaro, along with students and postdocs, focus on ensuring that high quality physics is enabled by the trigger and muon systems respectively. 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. For example, in 2014-2015 Dr. Savin led the Standard Model Physics Analysis Group (approximately 350 physicists and PhD students, up to 50 ongoing analyses) and Dr. Ojalvo (at Princeton from Sept. 2016) is leading the Tau Physics Object Group (approximately 50 members) since 2015. Under Dr. Savin's supervision the SMP group started 36 new analyses, published 22 and at the end of 2015 a further 15 were close to publication. Dr. Savin now serves as the Future Standard Model physics group co-convener. Our leadership roles span the physics organization and the upgrade physics program as indicated in section 7.

2.1.2 Proposed Research Directions

The primary mission of the LHC in Run 2 is the search for new physics. This includes 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. The UW group plans to continue its study of the SM Higgs boson and search for new Higgs bosons. We will also explore the nature of electroweak symmetry breaking by studying the phenomena of 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 has initiated a number of dark matter searches, which look for large missing transverse energy produced in association with SM particles such as photons and Z bosons. The group is also expanding this effort into searches involving Higgs bosons and exotic Z' bosons.

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 several important SM measurements at 8 and 13 TeV, from which searches for new physics are being launched. Under our direction, all graduate students are performing an EWK measurement in addition to searches for new physics phenomena. 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 (see Figure 1. These measurements have led us to new physics searches for additional Higgs bosons and dark matter.

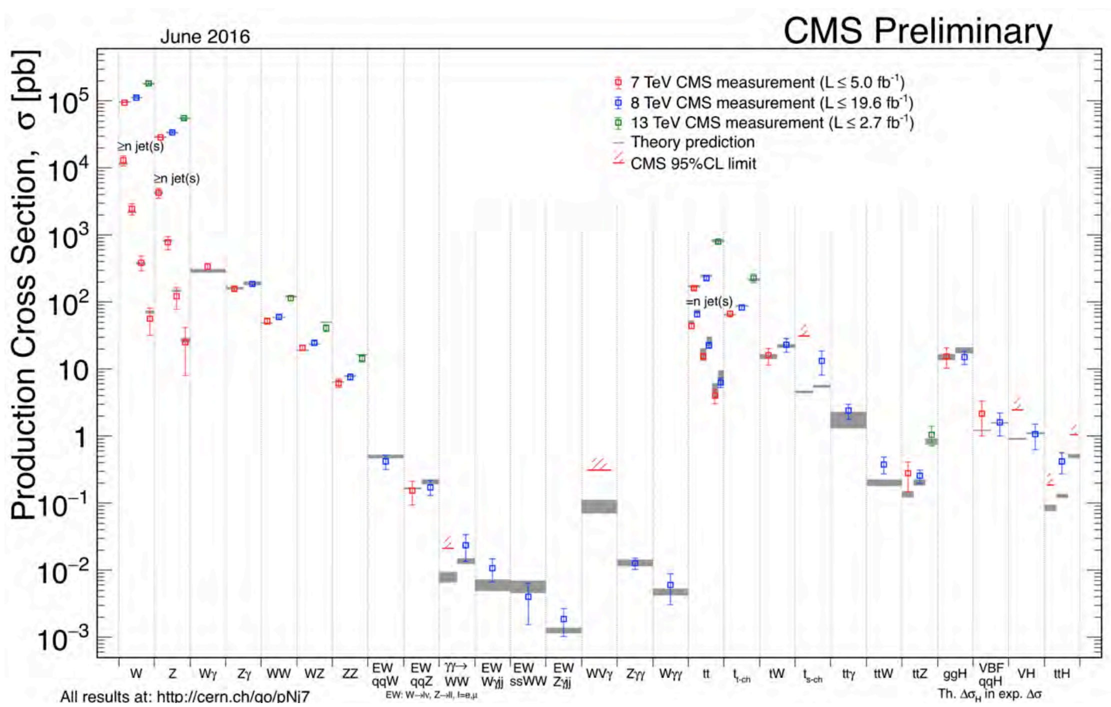


Figure 1. Measured production cross sections for various SM processes. Plot from Prof. M. Herndon.

2.2.1 Vector Boson with Jets

Our measurements of W bosons with heavy flavor jets addresses discrepancies between the experimental cross section and theory predictions, and establishes the critical background in Higgs searches in the H→bb decay channel. Following on a previous measurement of W+charm [4], Perry (Advisor Smith) Postdocs Cepeda and Ojalvo (Advisors Dasu and Smith), Scientist Savin, former Scientist Sarangi and Prof. Herndon performed measurements of W+2bjets (Figure 2) in both 7 and 8 TeV pp collisions [5,6]. Graduate student Levine (Ph.D. 2016, Advisor: Dasu) measured differential cross section for the production of a W boson in association with jets using 13 TeV data [7].

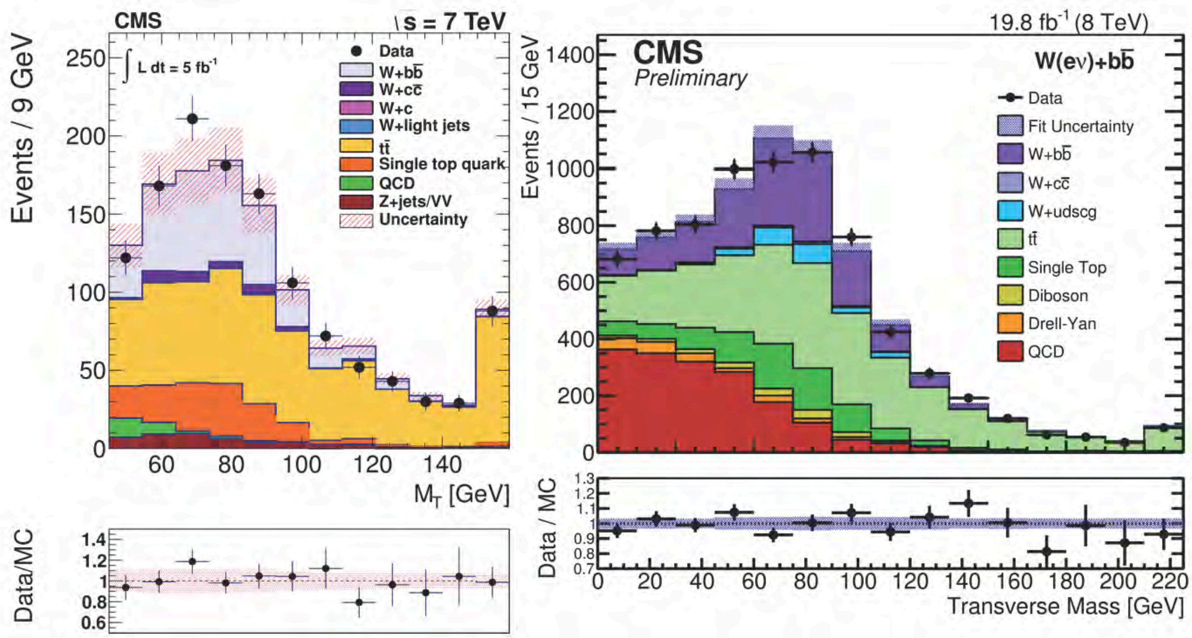


Figure 2. Transverse mass of the charged lepton and the neutrino in W decay in the W+2bjet analyses at 7 TeV (Ojalvo, left) and 8 TeV (Perry, right).

2.2.2 Di-boson Physics

In 2012-13, Prof. Herndon led and for 2016-17 Postdoc Duric (Advisor: Herndon) leads the multi-boson subgroup of the Standard Model Physics group. The multi-boson physics group studies di-boson production of vector bosons, anomalous triple gauge couplings (aTGCs) of vector bosons, quartic gauge couplings (aQGCs), and vector boson scattering. The group has more than twenty-five ongoing analyses. In addition, the group has strong 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. UW personnel are involved in all of these physics topics as described below.

2.2.2.1 WZ production in SM and anomalous couplings

Postdoc Duric (Advisor: Herndon) is an author of WZ property measurements using both 7 and 8 TeV [8] data with responsibility for aTGC searches. This work was performed in collaboration with the Rudjer Boskovic Institute, Croatia, the Instituto de F´ısica de Cantabria, Spain and other European groups. As part of this effort, Prof. Herndon and postdoc Duric have developed a framework for combining aTGC limits and Higgs couplings, which have overlapping sensitivity to aTGC. Also Dr. Duric has responsibility for overall combination of aTGC results within CMS and with ATLAS.

Graduate student Taylor (Advisor: Dasu) with Long (Advisor: Herndon), N. Smith (Advisor W. Smith), Woods (Advisor: Smith), Postdoc Duric, and Senior Scientist Savin have performed the first measurement of the WZ cross section at 13 TeV. Student 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. This measurement, the first of a diboson cross section at 13 TeV, has been submitted for publication [9]. A summary of the WZ cross-section measurements at 7, 8 and 13 TeV is shown in Figure 3.

2.2.2.2 ZZ production in SM

Following published measurements of the ZZ cross section at 7 TeV and an initial measurement of the cross section at 8 TeV [10] the UW group performed a more detailed study of the properties of ZZ production at 8 TeV [11] and a first measurement of the diboson cross section at 13 TeV. The 8 TeV measurements performed by graduate students Swanson (Ph.D. 2013, advisor: Smith) and Ross (Ph.D. 2013, advisor: Dasu) with Duric (Advisor: Herndon), and Senior Scientist Savin span both total and fully differential cross section measurements including leading Z transverse momentum, angular distributions, and M_{4l} as well as measurement of neutral aTGCs. Postdoc Duric has performed an aTGC combination including the four-lepton and in the 2l2ν decay modes, which have similar sensitivity [12]. This work was performed in collaboration with the Northeastern University Group and European collaborators. In addition Postdoc Duric has performed the first CMS+ATLAS combination of aTGC results in the ZZ channel [13]. Finally, graduate student Woods (Advisor: Smith) with graduate student Long and Postdoc Duric (Advisor: Herndon) and Scientist Savin have performed the first measurement of the ZZ cross section at 13 TeV [14], shown in Figure 3. Long contributed to the MC production and understanding of theory predictions, while Woods had the primary responsibility for the full analysis. This result has also been submitted for publication.

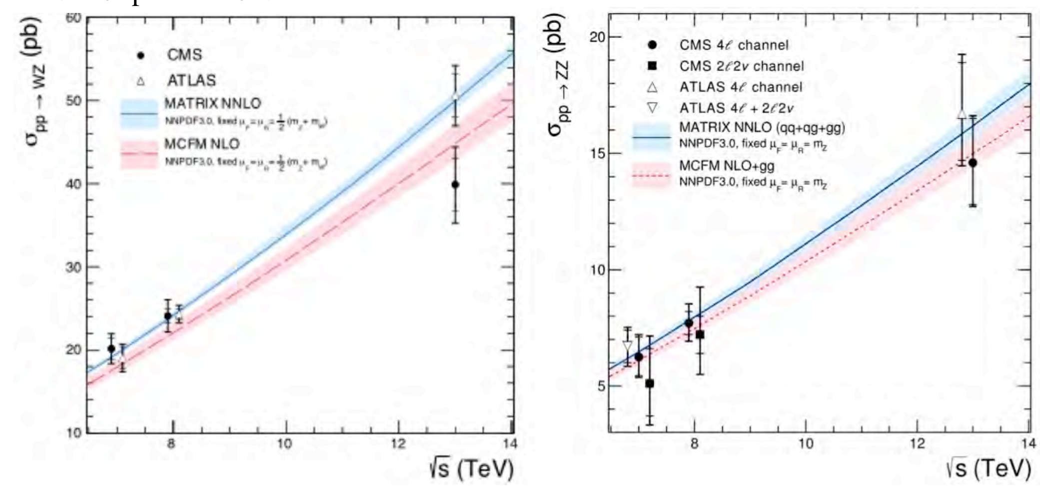


Figure 3. Measurements of the WZ (left, Taylor) and ZZ(right, Ross, Woods) cross sections as a function of pp center of mass energy. Plots by Long.

2.2.2.3 Zγ Analysis

Graduate students Buchanan (Advisor: Dasu), Perry (Ph.D. 2016, Advisor: Smith) and Postdoc Gomber (Advisors: Dasu and Smith) have performed cross section measurements and aTGC searches at 8 TeV and a preliminary cross section measurement at 13 TeV in the Zγ → ννγ channel. This exploits the higher statistics of the neutrino decay mode of the Z boson while maintaining good efficiency for events with high photon momentum and missing Et, which are most sensitive to possible aTGC contributions. The aTGC limits published at 8 TeV are the worlds most sensitive [15]. A preliminary first cross section measurement was performed at 13 TeV [16]. This work is leveraged to provide dark matter searches in the same topology (see below).

2.2.3 Proposed research: aTGC at NLO.

Postdoc Duric (Advisor: Herndon) set up a framework to investigate charged anomalous triple gauge couplings vs. NLO QCD predictions. This framework includes the ability to generate MC samples of both the SM production and anomalous contributions at NLO, and to apply NLO EWK corrections. The ability to employ both NLO QCD and EWK corrections is essential when investigating aTGC because the magnitude of the corrections can be large in high p_T and mass regions that are enhanced by anomalous contributions to the production process. This framework can also be used to investigate contribution to Higgs production and will be used with the full 2016 13 TeV data set.

2.2.4 Proposed research: Longitudinal vector boson scattering.

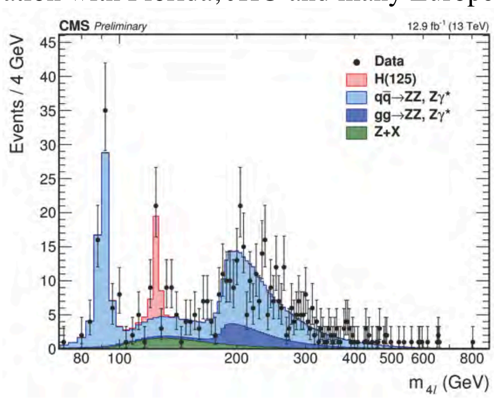
Postdoc Duric and graduate student Long (Advisor: Herndon) have begun a research program with the long-term goal of studying the mechanism of electroweak symmetry breaking through longitudinal vector boson scattering. They will study WZ production including forward tagged jets to identify vector boson scattering topologies. They will also study the WZ final state with additional jets at all rapidities to understand non-scattering sources of background. These measurements provide a test of new techniques in simulating diboson + jets final states at NLO and extend the work Prof. Herndon has performed in W^+W^- + jets[29] and Higgs at the Tevatron and WZ at the Tevatron and LHC. The initial analysis of the full 2016 13 TeV data set should have competitive sensitivity for quartic gauge boson interactions. Also the 3 charged lepton data set will be used to investigate the WWW final state. With additional data at 13 TeV collected in 2017 and 2018 we will study vector boson scattering via electroweak interactions. At higher luminosities the data will have sensitivity to the standard model rate of quartic gauge boson interactions in WZ, and possibly new physics contributions from heavy Higgs bosons or other new particles coupling to the gauge sector through longitudinal vector boson scattering. In addition, Postdoc Duric is investigating simplified models of di-boson decay to search for charged Higgs or additional charged vector bosons. Finally, Profs. Dasu, Herndon and Smith, along with new students, will explore vector boson scattering of Z boson pairs.

To study the potential of these final states, Prof. Herndon and student Long have performed generator level studies and a fast detector simulation of the SM signal, possible new physics contributions, and the primary background. This work is documented in [32], which is released as a CMS future physics study and benefits from collaboration with the Fermilab LHC Physics Center (LPC).

2.3 Higgs Physics

2.3.1 Higgs Decays to Z pairs in lepton modes

Graduate student Woods (Advisor: Smith) and Scientist Savin are primary Wisconsin contributors to the analysis of Higgs decays to Z-pairs in the four-lepton mode. The preliminary 12.9-fb^{-1} result presented at ICHEP 2016 [17], shown in Figure 4 shows rediscovery of H(125 GeV) at 6.2σ. After validating the 125-GeV resonance measurement, Woods and Savin focused on the high mass region, extending limits on production of additional scalar resonances with masses up to 2.5 TeV, with various widths. Graduate student N. Smith (Advisor: W.H. Smith) assisted in this analysis by providing lepton identification and isolation efficiency using the tag-and-probe technique. Earlier graduate students Ross (Ph.D. 2013, Advisor: Dasu) and Belknap (Ph.D. 2014, Advisor: Smith) and Scientist Savin, played an important role in the discovery of the lighter 125 GeV Higgs boson [2,3] using Run-1 data. Belknap had made an alternate study of the spin-parity of H(125 GeV) using angular distributions only, to provide a convincing measurement of the new boson's spin and parity. Woods will continue to analyze the full 2016 dataset to form the basis for his Ph.D. thesis through 2017. This work involves continued collaboration with Florida, JHU and many European groups.



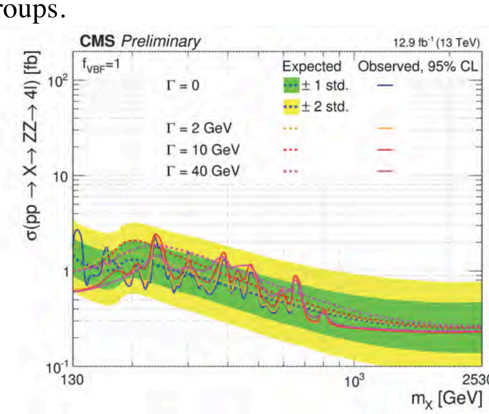


Figure 4. Four lepton invariant mass and upper limits at 95% CL on production of a high mass resonance decaying to four leptons via a Z-boson pair, including four-lepton branching fraction (Woods).

2.3.2 SM Higgs Decays to tau pairs

The SM decay $H\to\tau\tau$ provides access to the Higgs Yukawa couplings to the lepton sector. The UW team of graduate students Bachtis (Ph.D. 2012, Advisor: Dasu), Swanson (Ph.D. 2013, Advisor: Smith), Ojalvo (Ph.D. 2014, Advisor: Smith), Levine (Ph.D. 2016, Advisor: Dasu), former postdocs Friis and Ojalvo (Advisors: Dasu & Smith) and Scientist Savin made extensive contributions [18] 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 (UW), Current Convener Ojalvo) and the H2Taus Physics Analysis Group (Past Convener: Dasu). Bachtis' thesis won the CMS 2012 best thesis award. The Run-1 results [19], which involved many channels and categories jointly analyzed, culminated in a 3σ excess seen at M_H=125 GeV. 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.

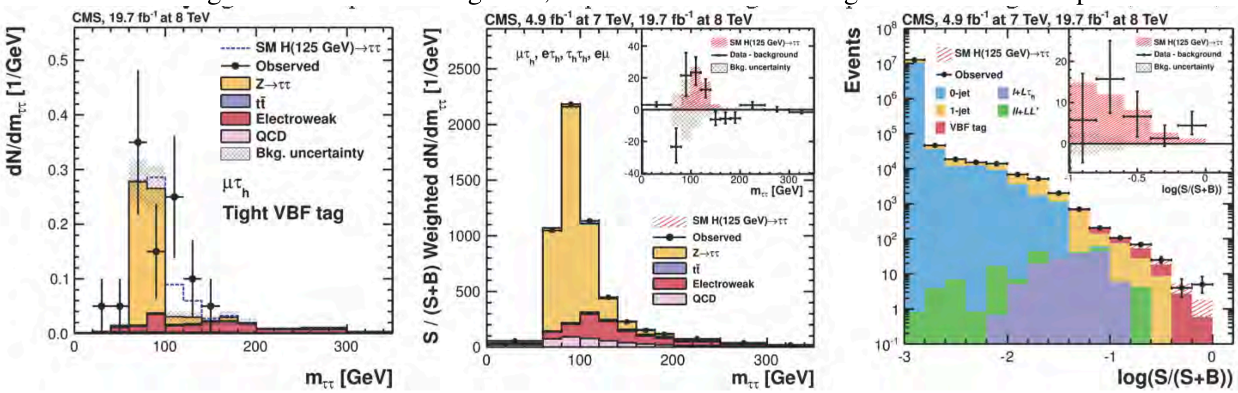


Figure 5. Most sensitive channel μτ VBF-tagged mass distribution (left), combined distribution for all channels and all categories for Run-1 (center). Individual channel significances (right) with an inset.

The quest for H→ττ continues with current graduate students Dodd (Advisor: Smith) focusing on $e\tau_h$ and $\mu\tau_h$ modes and Ruggles (Advisor: Dasu) focusing on eμ, $\tau_h\tau_h$ and W&Z associated production modes. New postdoc Caillol (Advisors: Dasu & Smith) is an important player in the H→ττ analysis, having contributed to W&Z associated production in the Run-1 analysis as a graduate student from Brussels. Dodd and Ruggles 2017 theses will likely provide much anticipated 5σ discovery, assuming that the H(125 GeV) is indeed the Standard Model Higgs boson.

2.3.3 Proposed research: SM Higgs Physics

Profs. Dasu and Smith, their jointly supervised Senior Scientist Savin and Postdoc Caillol, and Graduate students Laura Dodd (Advisor: Smith), Nate Woods (Advisor: Smith), Tyler Ruggles (Advisor: Dasu) and Devin Taylor (Advisor: Dasu) will continue their strong role in Higgs physics.

H(125) decays in four lepton state are very well reconstructed providing an ideal laboratory to study Higgs properties. Initial studies from Run-1 and Run-2 indicate that the H(125) is a scalar as is expected in the SM, but the full dataset from Run-2 (Woods thesis) will provide definitive statement on the spin-parity of this boson. That the H(125) coupling to fermions is at the appropriate level is important to establish that it is indeed SM-like, and is best measured in the τ-pair and b-pair modes. The τ-lepton trigger and reconstruction improvements championed by the UW group are particularly important and are likely to enable 10% level measurements using full Run-2 dataset (Dodd and Ruggles theses).

2.3.4 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 is continuing this search pursuing all four sensitive channels, with and without b-tagging, to enhance MSSM sensitivity. Preliminary results prepared using the limited 2015 dataset at 13 TeV [20], shown in Figure 6, already extend the reach beyond Run-1. However, much of the parameter space is still unexplored, and our efforts will continue. The UW MSSM Higgs team comprises current graduate students Dodd (Advisor: Smith) focusing on $e\tau_h$ and $\mu\tau_h$ modes and Ruggles (Advisor: Dasu) focusing on eμ, $\tau_h\tau_h$ and new postdoc Caillol (Advisors: Dasu & Smith) in collaboration with the same CMS group as SM Higgs to tau-pairs.

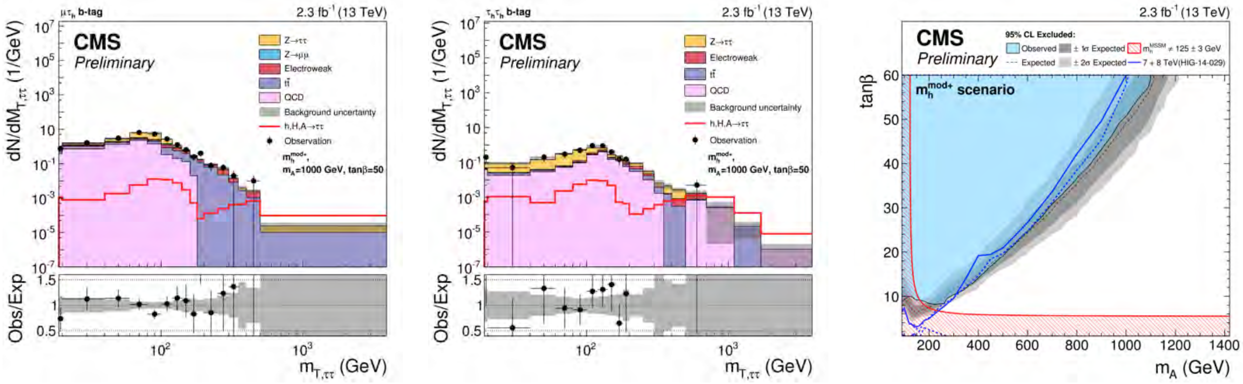


Figure 6: The di-tau mass spectrum for μτ and ττ channels, with b-tag, using 2015 data and 95% excluded region in the MSSM parameter space for a particular scenario, extending beyond Run-1 exclusion.

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. Graduate student Dodd and former postdoc 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). Graduate student Ruggles and new postdoc Calliol searched for A-boson in 2l2τ mode. Both these results were negative, yielding an exclusion region in m_A-tanβ plane. The UW group plans to continue all three of these MSSM searches in order to discover the MSSM Higgs sector, taking several hundred fb^{-1} to fully complete.

2.3.5 Light Pseudoscalar 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. New postdoc Caillol is continuing her searches 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 ready for publication. This will be continued by Caillol in collaboration with KSU, UCD and European groups.

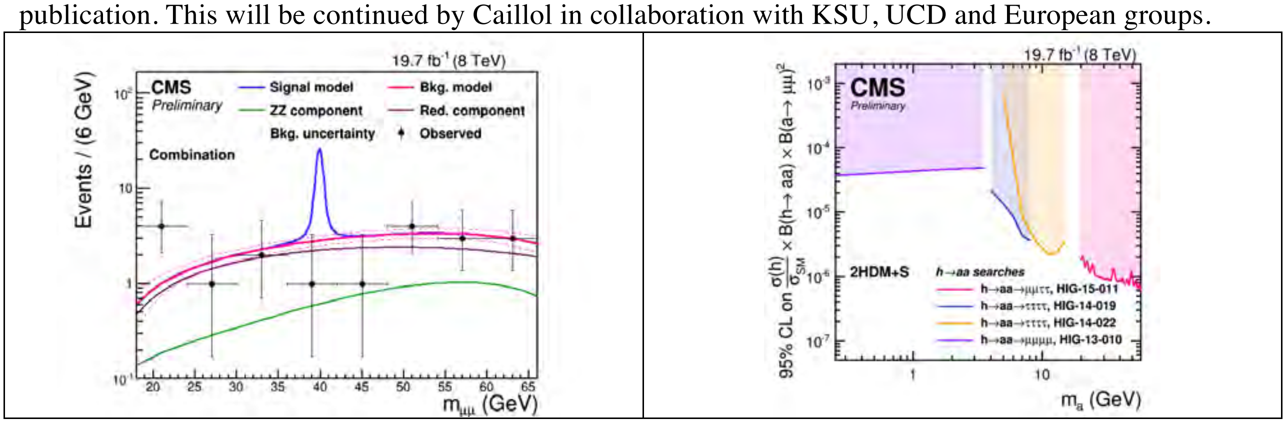


Figure 7: Measured invariant mass of muon pairs compared to predictions (left) and 95% CL exclusion limit on cross section times branching fractions as a function of a-boson mass (right).

2.3.6 Doubly Charged Higgs

In non-minimal Higgs models with a triplet state, doubly charged Higgs bosons occur. These models have a connection with neutrino mass sector. Discovery of doubly charged Higgs boson is a tell tale signature of new physics. Graduate student Taylor (Advisor: Dasu) is continuing his earlier studies made with past graduate student Belknap (Ph.D. 2014, Advisor: Smith) [21] using the 2016 13-TeV dataset. The Run-1 doubly charged Higgs candidate mass spectra and exclusion levels are shown along with the expected reach in Figure 8. The reach with the initial 2016 dataset is also shown.

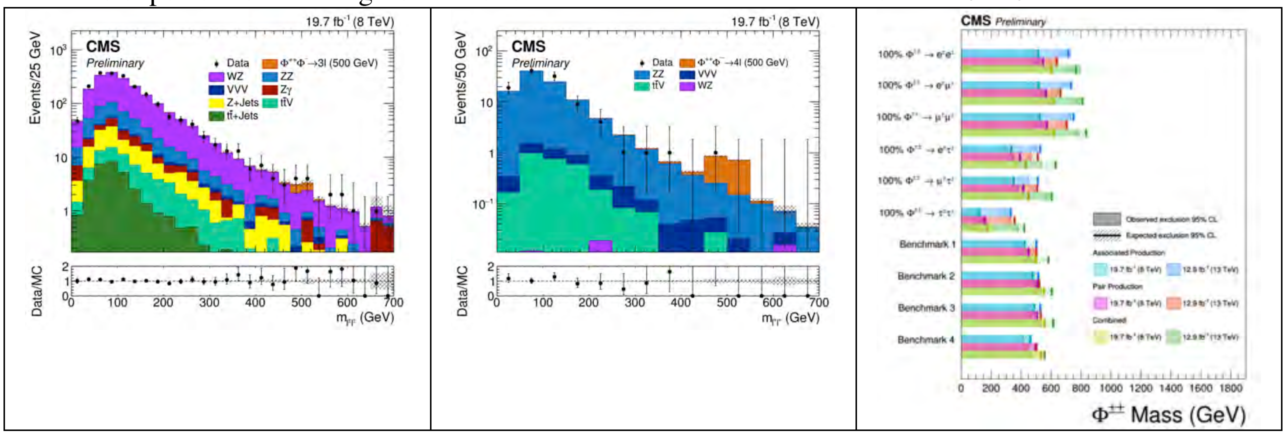


Figure 8: Like-sign lepton mass distribution for 3-lepton (left) and 4-lepton (center) selections and 95% CL exclusion limits plotted for various cases as a function of the doubly charged Higgs boson mass.

2.3.7 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 (Figure 9) [22] and [23], resulting in much speculation by the theory community. A quick follow up using 2015 data indicated that it is most probably a statistical fluctuation [24]. New postdoc Calliol, in collaboration with Notre Dame and CERN groups, will pursue the much-anticipated 2016 resolution of this issue.

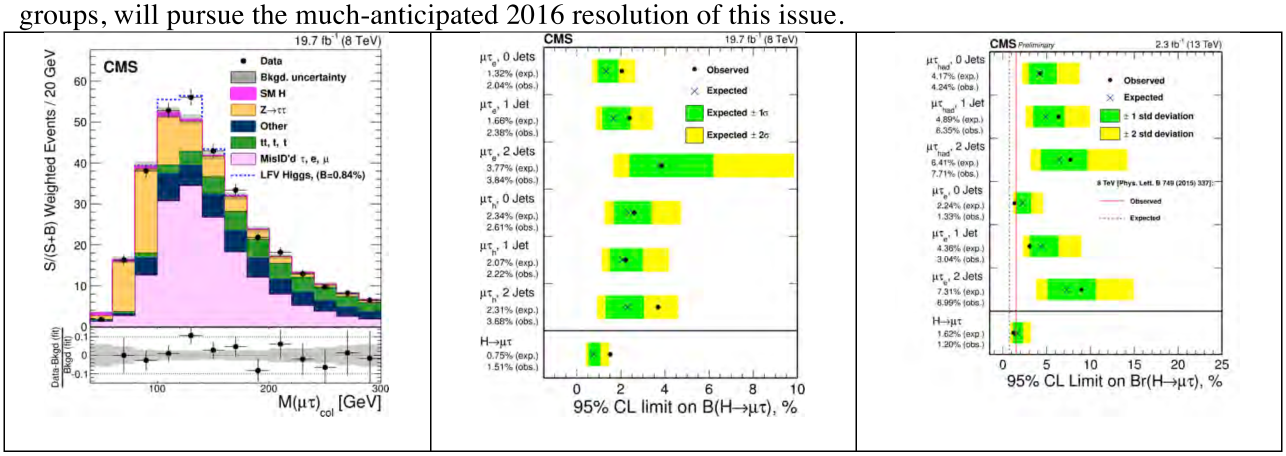


Figure 9: Collinear mass spectrum of muon and tau system (left), 95% CL Limit on H to μτ branching fraction using Run-1 data indicating small 2σ excess (center), and 2015 result consistent with SM (right).

2.3.8 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 postdoc Gomber (Advisors: Dasu & Smith) have searched for invisible Higgs decays using ZH associated production mode, where the Z-boson decays to light leptons [25,26]. 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.

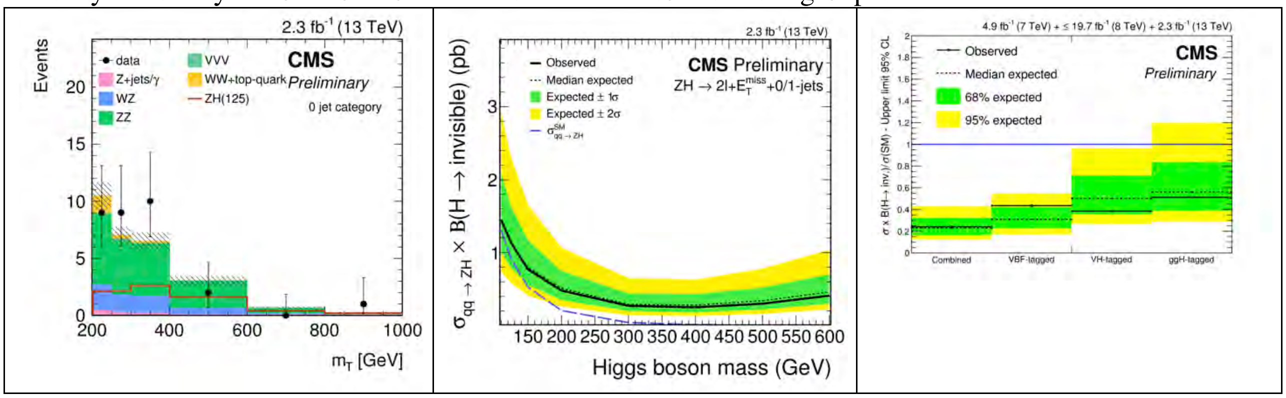


Figure 10: Transverse mass of Z(ll)+MET selection using 2015 dataset (left), limit on invisible-H cross section times branching fraction (center) and the combination all modes and all data through 2015.

2.3.9 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 closing the wedge in the M_A-tanβ plane by using the τ-pair search from above and H→hh and A→Zh modes from below.

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.

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 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. Our group has started analyzing the Run-2 data in four types of singly produced recoiling particles, with some initial results presented at 2016 conferences.

2.4.1 Mono-γ Analysis

Graduate student Buchanan (Advisor: Dasu) and postdoc Gomber (Advisors: Dasu and Smith) searched for mono-γ signature in both 2015 [27] and early 2016 [28] data. The photon and missing transverse energy spectra shown in Figure 11 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 such as LUX. 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.

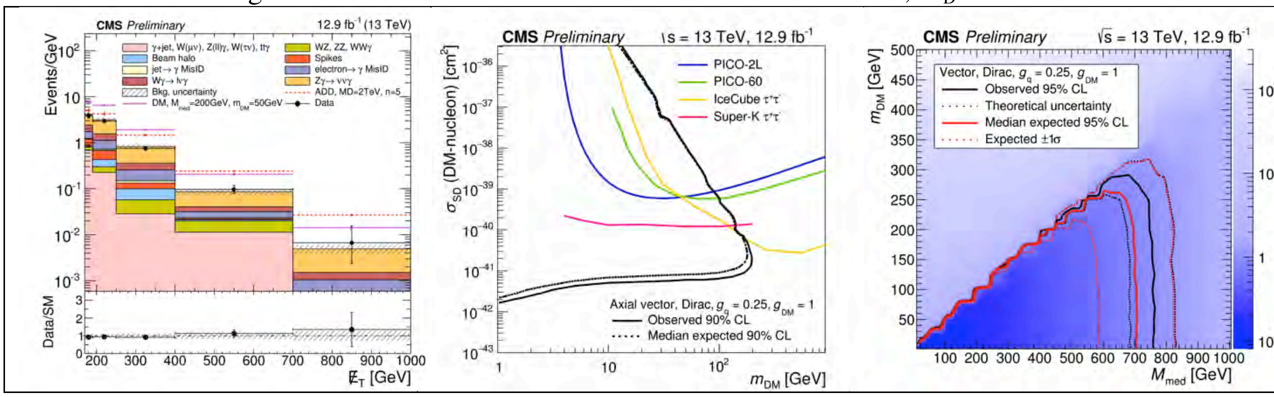


Figure 11: The missing E_T spectrum (left) for mono-photon event selection, 90% CL limits on dark matter-nucleon interaction cross section for axial vector (center) couplings in comparison to direct search experiments and exclusion region in mediator versus dark matter mass space (right) are shown.

2.4.2 Mono-Z Analysis

Graduate student N. Smith (Advisor: W.H. Smith) and 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 [29] and 2016 [30] data. The results are consistent with the expected background from the Standard Model processes, dominated by the Z(*ll*)Z(νν) process at high E_T^{miss}. 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 as shown in Figure 12.

2.4.3 Mono-H Analysis

Graduate student Dodd (Advisor: Smith) and postdoc Gomber (Advisors: Dasu and Smith) have recently begun a mono-higgs analysis. They are using our group's expertise in the study of SM Higgs boson decays to τ-pairs, to search for such H(ττ) candidate recoiling from large missing transverse energy. The connection of the Higgs boson with the 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 bosons (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. Initial results obtained by our group using the τ-pair channel are promising as shown in Figure 12 and compare favorably to the b-pair channel recently reported at ICHEP.

2.4.4 Mono-Z' Analysis

Graduate student Hussain (Advisor: Smith) and postdoc Gomber (Advisors: Dasu and Smith) 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 think pencil-like jet recoiling from a large missing transverse energy is produced. The pencil jet finder and analysis framework is being set up. Early results are quite promising as shown in Figure 12.

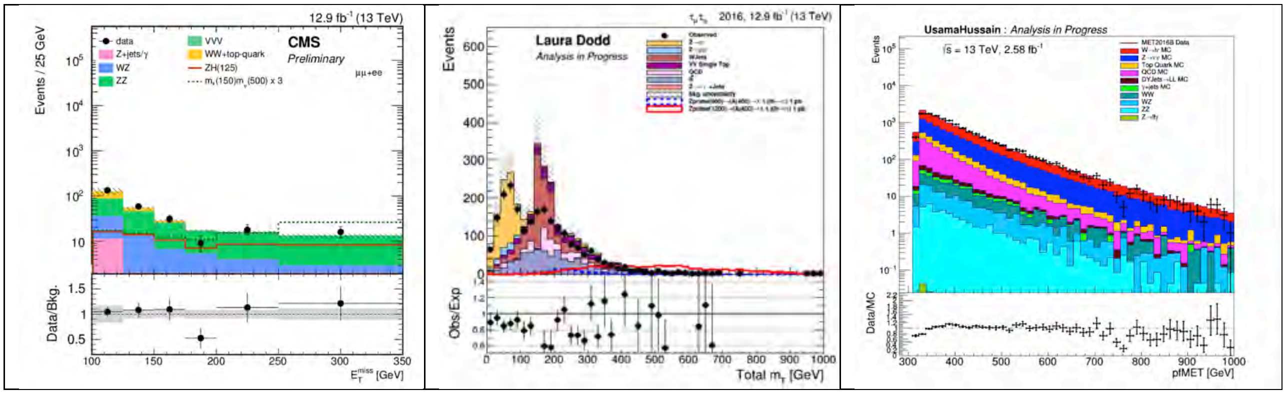


Figure 12: Signal region spectra of E_T^{miss} for mono-Z selection (left), transverse mass distribution of τ-pair + MET for mono-H selection and E_T^{miss} for mono-Z' pencil-thin jet selection indicating good agreement with SM background predictions.

2.4.5 Proposed Research: Dark Matter Searches

Profs. Dasu and Smith, their jointly supervised Postdoc Bhawna Gomber, and Graduate students James Buchanan (Advisor Dasu), Usama Hussain (Advisor Smith) and Nick Smith (Advisor W. Smith) will continue their strong role in searches for weakly interacting massive particle Dark Matter searchers.

2.4.5.1 Mono-Photon and Mono-Z Searches

Anomalously high production of missing transverse energy, compared to the SM predictions, in events with 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 preliminary results from 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 underway (LUX, PandaX, Xenon) or planned for near future (LZ). Our group intends to pursue this line of searches with the full Run-2 data and beyond.

2.4.5.2 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. Therefore, we are pursuing the invisible Higgs decay channel vigorously. We look for anomalous production of MET accompanied by Z bosons that decay to a pair of electrons or muons. This channel is likely to remain available for exploration for all of Run-2. In models with 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. The h(125) decay in the t-pair channel is sufficiently clean to provide a strong search possibility, which our Higgs (Dodd) and DM (Gomber) teams are exploring together. In other models with light Z's, low multiplicity Z' decays (pencil jets) can be seen recoiling from anomalously large MET. We anticipate that Run-2 data will provide a good discovery reach for all of these channels and are intent on pursuing them.

2.5 Physics Analyses Service

Profs. Dasu and Herndon, and Scientists Lanaro, Klabbers, Savin, former Scientist Loveless, postdoc Duric and former postdoc 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.

2.6 Fermilab LPC Activities

The faculty and junior students based at Wisconsin take part in Fermilab LPC activities regularly. The junior students participated in the CMS Data Analysis School, HATS@LPC and other workshops to learn about CMS, its software and analysis techniques. Postdoc Gomber organized two tutorials for CMSDAS. Profs. Smith and Dasu have lectured on CMS trigger at such schools several times. Prof. Herndon has a strong collaboration with the SMP team at LPC. In the spring and summer of 2014 Prof. Herndon developed and taught a workshop course on tracking and large-scale reconstruction software development while on leave at Fermilab. The course was sponsored by the Fermilab Computing Division and organized by the LPC. Prof. Dasu organized several LPC events, collaborates with LPC scientists on trigger projects and serves on the LPC management board.

2.7 MBI 2016

In August 2016 UW Madison hosted the Multiboson Interactions (MBI) 2016 workshop. This is the 4th annual meeting of this workshop, which brought theorists and experimentalist together to discuss multiple boson physics. This year Prof. Herndon was the chair of the organizing committee. There was substantial participation in both organization and attendance from the Fermilab LPC and Theory group.

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. 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. Upgrades to the LHC now in place have the potential to exceed a 50% increase of the LHC design luminosity, while the CMS L1 trigger rate remains limited to 100 kHz by the readout electronics. This necessitated the Phase 1 upgrade to the L1T, successfully installed in two stages in 2014 and 2015 and now fully operational for the 2016 run. For the HL-LHC running, planned to start in 2024, the luminosity is planned to exceed 5×10^{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.

As the CMS Trigger Project Manager from 1994 to 2007 and the CMS Trigger Coordinator from 2007 until July 2012, Prof. Smith had overall responsibility for the design, construction and operation of the online L1 and Higher Level Triggers through the discovery of the Higgs Boson. Prof. Smith then co-convened the CMS Trigger Performance and Strategy Working Group that developed the long-term trigger strategy and architecture for the HL-LHC upgrade after 2024 and wrote the Trigger Chapter of the CMS Technical Proposal for the HL-LHC upgrade. Prof. Smith remains the US CMS Level-2 Manager for the Trigger since 1997 with responsibility for US maintenance, operations and updates/optimization of the calorimeter and muon triggers as well as the Higher Level Triggers. From the start of LHC data taking through the Phase-1 upgrade, the operational performance of the US CMS calorimeter and endcap muon trigger systems has been superb, with negligible downtime, high signal efficiencies and stable rates. As the US CMS Level-2 Manager for the Phase 1 trigger upgrade Prof. Smith successfully led the US CMS Trigger Group through its construction, installation and commissioning completed in 2016. Prof. Smith is also now serving as the US CMS Level-3 Manager for the HL-LHC calorimeter trigger upgrade.

Prof. Dasu was responsible for the design and simulation of the original and the phase-1 L1 calorimeter trigger systems. Prof. Dasu continues to serve as the US-CMS Level-3 Manager for the Calorimeter Trigger. Prof. Dasu served as the original online selection group convener, which designed and implemented the original High Level Trigger system for CMS based on the standard offline software. He continues to advise the trigger studies group that operates this system.

UW Scientist Dr. Pamela Klabbers is the Trigger Technical Coordinator, sharing the oversight of the CMS trigger operations. This includes assessment and certification of the quality of data taken for physics analysis from the trigger viewpoint and taking actions on the trigger system to assure this quality.

Her responsibilities include coordinating on-call expert and daily shift schedules during operations with beam, coordination of the technical stop activities, chairing weekly meetings organizing trigger operations, and analyzing changing conditions that necessitate changes or repairs to the trigger.

UW Senior Scientist Savin is Convener of the Future Standard Model Physics Subgroup of the CMS Upgrade Studies Group, and has taken on the additional role of designing the upgraded calorimeter trigger system for the HL-LHC. In the past Dr. Savin was responsible for the trigger data quality management both for L1 and HLT systems, serving as Level-3 manager in the trigger studies group.

3.2 Calorimeter Trigger and its Phase-1 Upgrades

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. In an unprecedented level of achievement, during the years 2014-2016, the UW group successfully operated 3 different calorimeter trigger systems, running two at a time in parallel and built, installed and commissioned two of these trigger systems involving new 85 electronics boards with two FPGAs apiece and more than a thousand high-speed optical links. The original schedule of the Phase-1 trigger upgrade was broken into two stages to provide an immediately partially upgraded trigger when running resumed after LS1 in 2015 and the full system completion date was advanced due to anticipated increases in LHC luminosity and the need to keep thresholds low to maximize statistics for Higgs studies.

The original CMS Level-1 e/γ, τ, jet, and missing transverse energy trigger decisions were based on the processing of the UW-built Regional Calorimeter Trigger (RCT), which received input from the CMS hadron calorimeter (HCAL) and electromagnetic calorimeter (ECAL), and the hadron calorimeter in the very forward region (HF). The RCT's more than 300 9Ux 400 mm custom VME cards with UW-built custom high-speed backplanes used a deadtimeless parallel pipelined architecture that processed 2 Terabits/sec of HCAL, ECAL and HF data on copper cables from 40 MHz of crossings and forwarded the found electron/photon, jet, and tau candidates to the Global Calorimeter Trigger (GCT) for refining, sorting and transmission to the level-1 Global Trigger.

Figure 13 shows the splitting of ECAL and HCAL dataflow between new and old trigger systems. The upgraded ECAL provides an optical input path with duplicate information to the RCT and Upgrade Calorimeter Trigger (UCT). This required 574 new mezzanine cards (oSLB) on the ECAL Trigger Concentrator Cards (TCCs) to convert the output to optical format and 574 optical Receiver Modules (oRM) installed on the RCT Receiver cards and tested and commissioned by UW Scientist Klabbers, former postdoc Ojalvo and UW students and engineers in 2014 with connecting fibers and patch panel/splitter to provide an additional output to connect to the UCT so that both systems could be operated in parallel with physics data during the transition period. Due to an upstream split, the upgraded HCAL electronics was operated in parallel with the original HCAL electronics, connected to the RCT and UCT, respectively.

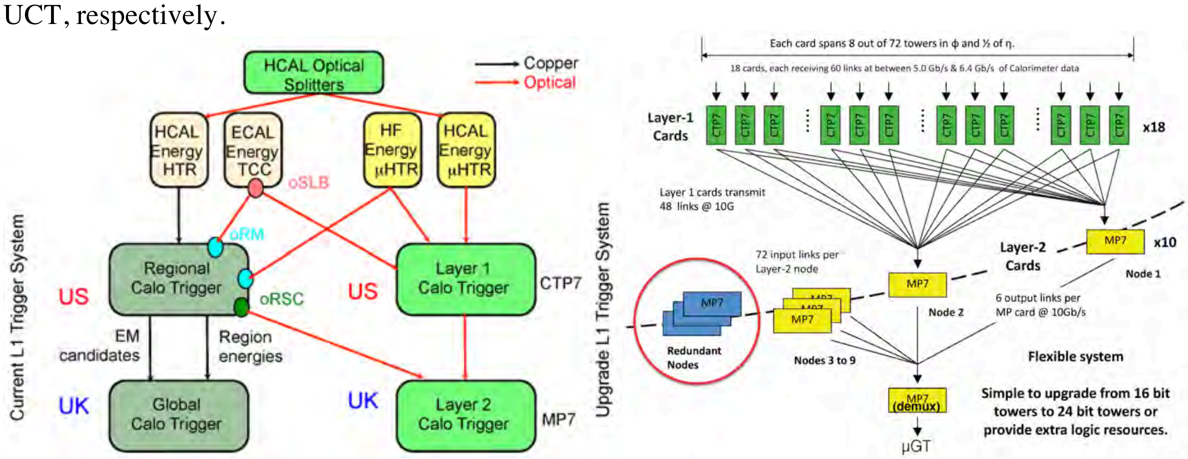


Figure 13. Left: Dataflow for upgraded Level-1 calorimeter trigger. Right: Detail of trigger layers.

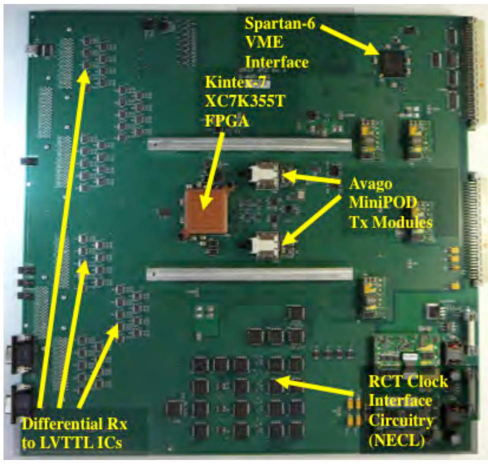


Figure 14. ORSC Card.

The original calorimeter trigger was modified for 2015 running as a first stage of the UCT (Stage-1), essentially replacing the GCT with preproduction upgrade prototype hardware. The RCT was reprogrammed to provide two types of clusters. The UCT Stage-1 processor received all the RCT data in one card to implement the improved algorithms. The cluster data from the original RCT crates was converted from 80-MHz differential ECL copper links to optical format using a new VME card, the oRSC, shown in Figure 14. Eighteen UW-designed and built oRSCs, one per RCT crate, were installed to serve all the data to the UCT with the UW UCT Stage-1 CTP7 (see below) used for readout. The new system provided upgraded trigger algorithms on the evolutionary path to the full UCT, but at the very beginning of the 2015 running. It also provided early valuable operational experience with the new Phase 1 trigger electronics used for Stage-2 that enabled a faster commissioning and start of operations of the final Phase 1 calorimeter trigger.

Under the leadership of Dr. Klabbers, the RCT was operated during the entire 2015 physics run with high performance and efficiency. The Stage-1 of the UCT successfully operated in parallel with the existing RCT system until it became the main calorimeter trigger in Sept. 2015 and provided for the first time per-event pile-up subtraction in Level-1 triggers. This method developed by UW Prof. Dasu with former postdoc Isobel Ojalvo and student Laura Dodd uses the number of regions with non-zero E_T, which as shown in Figure 15 is well correlated with the number of primary vertices which measures pile-up. Using algorithms developed by UW with groups from Fermilab, MIT and Rice, the performance in pp-running was considerably improved, for example, with tau triggers calculations using a reduction of more than 4 in feature size experiencing a 50% increase in efficiency to 95% and a factor of 10 reduction in rate as shown in Figure 15. This system also enabled an efficient trigger menu for 2015 Heavy Ion running, which was not possible with the original trigger designed for lower HI luminosity.

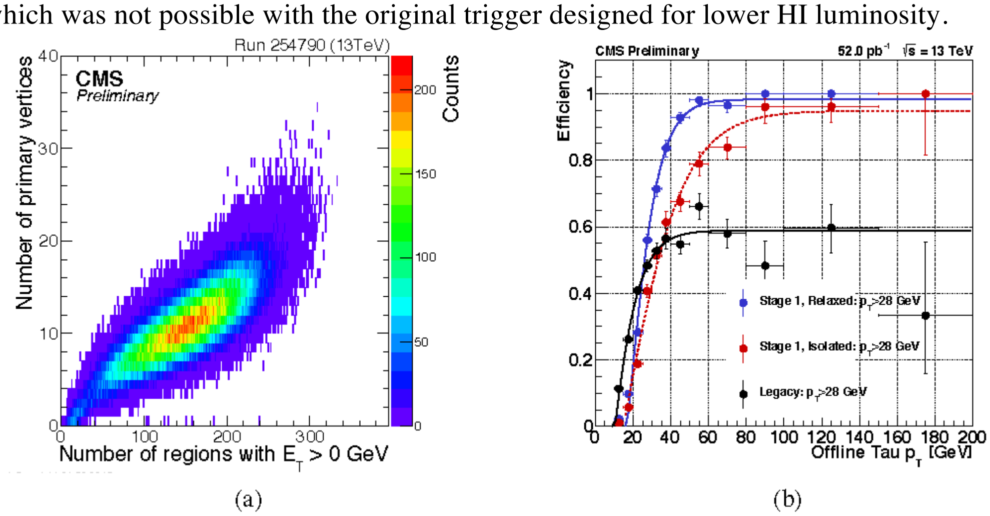


Figure 15. Phase-1 Stage-1 Calorimeter trigger upgrade: (a) Correlation between the number of regions with nonzero E_T and the number of reconstructed primary vertices in Run 2 data. (b) Isolated and relaxed (no isolation requirement) tau trigger efficiency as a function of offline transverse momentum (p_T) for an online requirement of $p_T > 28$ GeV. The Run-1 efficiency for taus is shown for comparison. Note that in Run-1 di-tau triggers also used the di-jet sample since the rate could be accommodated.

Figure 16. CTP7 Card with Virtex-7 and ZYNQ FPGAs

Working with Profs. Smith and Dasu, the Calorimeter Trigger Processor card (CTP7) shown in Figure 16 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 first layer of the final Phase-1 Upgrade Calorimeter Trigger (UCT) system. 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.

As shown in Figure 13 the Stage-2 UCT 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 successfully operated in CMS along with the optical patch panel as a parallel system with the Stage-1 UCT starting in Sept. 2015 (21 months after receipt of the first prototype board) and Stage-2 became the main calorimeter trigger in 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. The Stage-2 UCT system is shown in Figure 17.

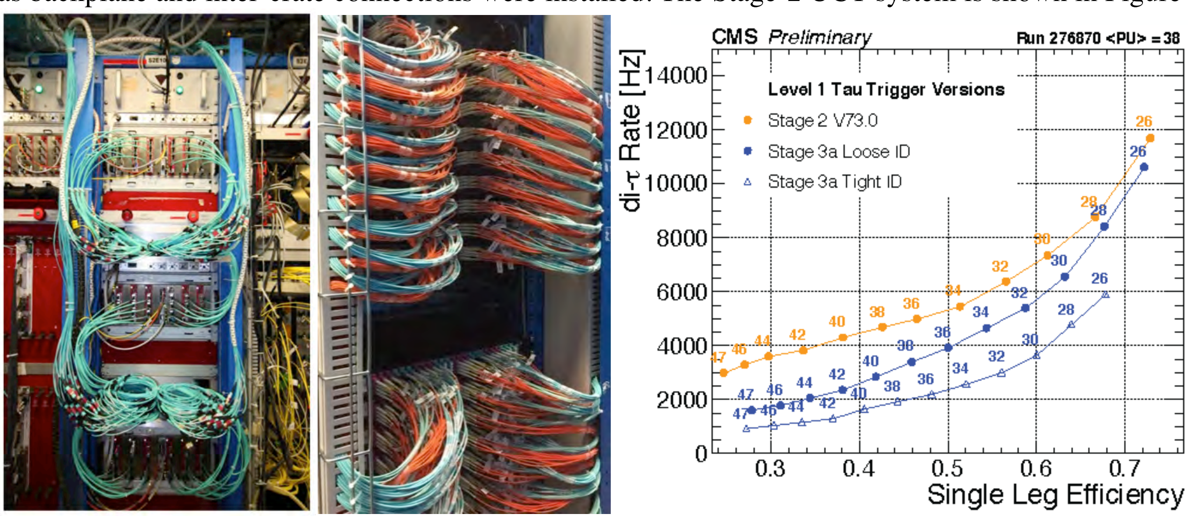


Figure 17. Left: Front of L1CT installation. Center: Rear of L1CT installation showing calorimeter fibers. Right: DiTau rate vs. single leg efficiency for the baseline Phase 1 upgrade (Stage-2), with additional algorithms (Stage-3) under study showing significant rate reductions at the trigger thresholds shown.

Since the luminosity is planned to increase, the UW group proposes continued development of new trigger algorithms using the Phase 1 upgrade hardware to be able to capture the physics signals over the next few years. 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 Stage-2 tower-level data. We plan adiabatic improvements to the calorimeter trigger (Stage-3a, 3b and 3c), which are capable of providing unique capabilities utilizing clusters found by Layer-1. Under the direction of Profs.

Smith and Dasu, UW scientist Klabbers is leading an effort with postdoc Bhawna Gomber and UW students, focusing on improving pile-up subtraction, more robust e/γ identification and better techniques of tau isolation (Stage-3a and 3b). Possibilities for muon-tagged b-jets exists with Stage-3c, using muon tracks provided by the level-1 track-finders. Example Stage-3a results are able to reduce tau trigger rates as shown Figure 17. 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.

3.3 Calorimeter Trigger Operations

The UW L1CT operations effort is led by Scientist Pamela Klabbers, and CMS project supported UW Electronics Engineers Tom Gorski and involves postdocs Cecile Calliol and Bhawna Gomber, students James Buchanan, Laura Dodd, Usama Hussain, Tyler Ruggles, Nick Smith and Nate Woods, as well as US CMS project supported engineers Ales Svetek (firmware), Marcelo Vicente (firmware), Jesra Tikalsky (software). This team maintains the trigger hardware at Point 5, a testing facility in the CMS Electronics Integration Center, for repair, upgrade testing, and software development, and the large base of continuously evolving software and firmware.

We review the L1CT 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 L1CT electronics modules, cables, power supplies and system components. Since the L1CT is a critical item for CMS during running, at least one UW L1CT expert is on call 24 hours a day.

The development of the L1CT 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 L1CT 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 Gomber (supervisor) and students Dodd, Smith and Buchanan have developed the emulator and are maintaining it and checking system performance with physics data, as well as using it to update the L1CT calibration and improve the calorimeter trigger performance.

The UW group also provided and now maintains the new interface between the new CMS Run Control Trigger system, called SWATCH and the L1CT. 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 L1CT hardware. This task is taken by Postdoc Caillol (supervisor) and students Ruggles, Woods and Hussain, under the overall supervision of P. Klabbers.

The CT 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 analyze the offline data using detailed histograms and checks to determine if the L1CT function meets the criteria to declare the run usable for physics.

The set-up and parameters of all the programmable aspects of the L1CT, 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 L1CT emulator so that it can duplicate the function of the hardware in the simulation. Postdoc Gomber with students Buchanan and N. Smith are updating and will maintain these databases both online and offline, under the overall supervision of P. Klabbers.

In parallel with the operations work we are also evolving the algorithms, firmware and software to cope with luminosity increases, continuing these improvements for the rest of Run-2.

3.4 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.

Prof. Smith 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 (CT) receives input data on optical fibers from the ECAL barrel (EB), HCAL barrel and endcap calorimeters, and the high-granularity calorimeter (HGC). The granularity of the EB and HGC 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 correlator 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.

Under the leadership of Senior Scientist Savin, postdoc Caillol and students Ruggles and N. Smith 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. Figure 18 shows 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.

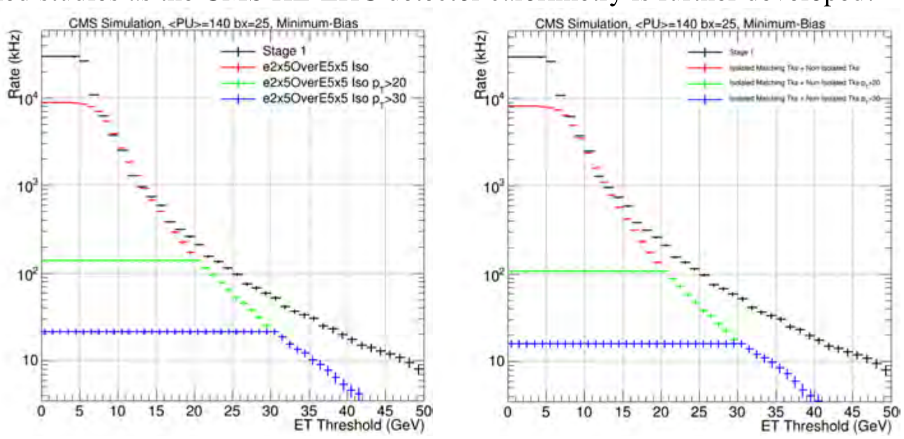


Figure 18. HL-LHC simulation with 140 pileup comparing rates for the Phase-1 Stage-1 calorimeter electron trigger with HL-LHC standalone EB full crystal geometry trigger (left) and the same trigger with a track match (right) for comparable efficiencies.

We are also engaged in two specific HL-LHC hardware activities informed by the algorithm studies. First, we are using the existing CTP7 hardware in test setups to investigate the firmware performance to implement the algorithms, evolution of the embedded Linux processing to provide detailed real-time link and system monitoring, improved protocols for higher data throughput and new devices for higher data-bandwidths. We also delivered and supported CTP7-based HL-LHC development hardware systems to CERN and Cornell for the HL-LHC L1 tracking trigger, to CERN for EB HL-LHC readout R&D with Notre Dame, Rutgers and U. Virginia and to both CERN and Texas A&M for EMU HL-LHC R&D (resulting in adoption of the CTP7 for the GEM GE1/1 μTCA-based backend processing board). Additional setups and a second production of CTP7s are anticipated. Thus the UW group is supporting a significant part of the US CMS HL-LHC R&D electronics program with the CTP7 setups.

Led by Profs. Smith and Dasu, the second HL-LHC trigger activity is for the US CMS-supported UW engineering team of Gorski (design) Svetek and Vicente (firmware), and Tikalski (system software) to build a series of prototypes leading towards the eventual production of electronics boards for the US-CMS HL-LHC calorimeter and correlator trigger projects. UW Scientists, postdocs and students will be involved in testing and evaluation. The first version of the Advanced Processor (AP1) will be a general purpose ATCA (Advanced Telecommunications Architecture) FPGA (e.g. Xilinx Ultrascale/+) processing platform planned for 2017, with additional refined cards to follow, leading to a demonstration system in 2019. The initial requirements are 100 optical connections that are multi-rate capable to accept inputs from different calorimeters as well as accept and drive up to 25 Gbps. The cards will feature expansion mezzanines and application-specific Rear Transition Modules for large memory look-up tables or a supplemental FPGA processor, embedded linux (e.g. ZYNQ), customizable I/O capability for legacy interfaces and backplane and fiber-optic fabrics

4 Muon System Activities

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, 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 performance simulation.

UW Senior Scientist Dr. A. Lanaro is the CMS Project Manager for the CSC system since Sept. 2015, and the US CMS Deputy EMU L2 Project Manager. UW Distinguished Scientist Dr. R. 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 Muon program, supervising Postdoc Duric and graduate students Taylor (Advisor: Dasu) and Long working at CERN on CSC re-commissioning during LHC long shutdown 1 (LS1) in preparation for the Run 2 data taking, EMU maintenance in LS1, and operation and data analysis in Run 2, in addition to HL-LHC R&D.

4.1 Endcap Muon System Consolidation and Maintenance in LS1 (2014-15)

The ME4/2 project completed the fourth forward muon station in 2011-14. An international team of ~20 people led by Dr. Lanaro constructed, tested, installed and commissioned, during LS1, 72 new CSCs. As CSC technical coordinator Dr. Lanaro supervised the integration and commissioning of the newly refurbished ME1/1 chambers and of all the existing CSCs in CMS. Postdoc Duric and graduate student Taylor actively participated in all phases through the final commissioning in CMS. In May 2015 the whole EMU system was declared "ready for collisions". Thanks to work performed in LS1 on consolidation, maintenance and repairs of detectors and infrastructure, the EMU system entered Run 2 with 18% additional CSC channels (compared to Run 1), from the ME1/1 and ME4/2 upgrades, and 99.5% efficiency (for live channels), as shown in Figure 19.

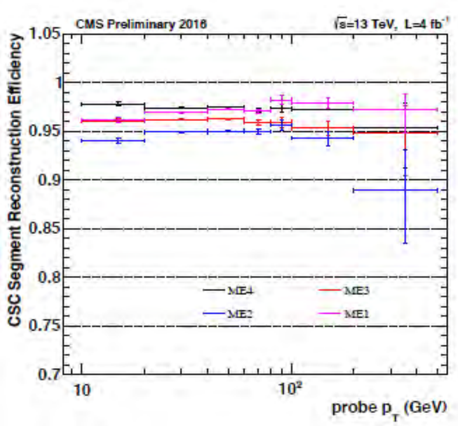


Figure 19. CSC muon track segment reconstruction efficiency vs. muon p_T (2016 data).

4.1.1 Endcap Muon System Run 2 Operation

Since the start of Run 2 (2015-2016), the UW EMU group continued its responsibility for the monitoring of the performance of the CSC system and the validation of the quality of recorded data. Since Sept. 2015, Postdoc Duric is the Detector Performance Group (DPG) coordinator responsible for "Data Monitoring and Detector Performance", coordinating the activity of a dozen students and post-docs. Meanwhile, student Long has become 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. These are tasks UW has been institutionally responsible for since the beginning of LHC running. Studies carried on by Postdoc Duric and her co-workers have established the excellent performance of the CSC system with 2015 and 2016 data, confirming the performance already established in Run 1. Muon reconstruction efficiency (Figure 19), trigger efficiency, detector time and space resolution have been remarkably stable throughout Run 2, in spite of numerous changes to optimize the timing, synchronization and tracking algorithms.

Postdoc Duric and graduate students Taylor and Long serve 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.

4.2 Endcap Muon System Plans for 2017-19 and beyond

The UW group will play a major role in maintaining high detector efficiency for recording high quality data for physics analyses throughout the lifetime of the experiment and we 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.

After LS3, the HL-LHC accelerator upgrade will set new challenges for CMS and EMU. The UW group will work on the redesign of the forward muon region to exploit the increased LHC performance while operating in the challenging radiation environment of the HL-LHC as described in section 4.2.2.

4.2.1 EMU Plans for Operations and DPG

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) and increased granularity. In DPG, Postdoc Duric is working to improve muon identification in higher background and pile-up conditions. The track segment reconstruction of high p_T muons is of paramount importance since muon momentum resolution at high p_T is determined by the forward muon reconstruction. The UW group will study methods of mitigating muon showering, a dominant effect degrading reconstruction accuracy.

4.2.2 EMU Eco-friendly Gas and R&D on Longevity Studies for HL-LHC

The UW group is involved in investigating solutions for operating the EMU system with an eco-friendly gas mixture in anticipation of more restrictive environmental EU-regulations for gas emissions. Senior Scientist Lanaro is coordinating the construction at CERN of small-size CSC prototypes for studying novel gas mixtures with reduced or complete replaced CF4. The project will have 2 phases: 1) 2017-18 detector performance studies with new gases establishing their operation parameters and 2) 2018-19 for the selected gas assess the longevity of the CSC detectors with irradiation tests at the CERN new Gamma Irradiation Facility (GIF++). Dr. Lanaro is also coordinating a similar R&D effort at St. Petersburg (PNPI). UW students will work on the CERN testing program.

Anticipating running at high luminosity, Senior Scientist Lanaro is leading the EMU group in a campaign of aging studies aimed at establishing CSC detector longevity for long-term operation at the HL-LHC. The project was first proposed and then coordinated by Dr. Lanaro with the strong involvement of Posdoc Duric (infrastructure, DAQ and operation) and graduate student Long (operation, monitoring, measurements and analysis). The goal is to accumulate a charge equivalent to 3000 fb^{-1} of HL-LHC operation, with a safety factor 3. The irradiation of 2 CSCs has started in Feb. 2016 at GIF++, Figure 20.

Availability at GIF++ of a muon beam in addition of the gamma irradiation provides a very useful benchmark for studying CSC electronics, DAQ and trigger responses to muons in a very high background rate environment, representative of that expected at the HL-LHC. This allows studies of chamber performance (efficiency and resolution) with different reconstruction software algorithms, in

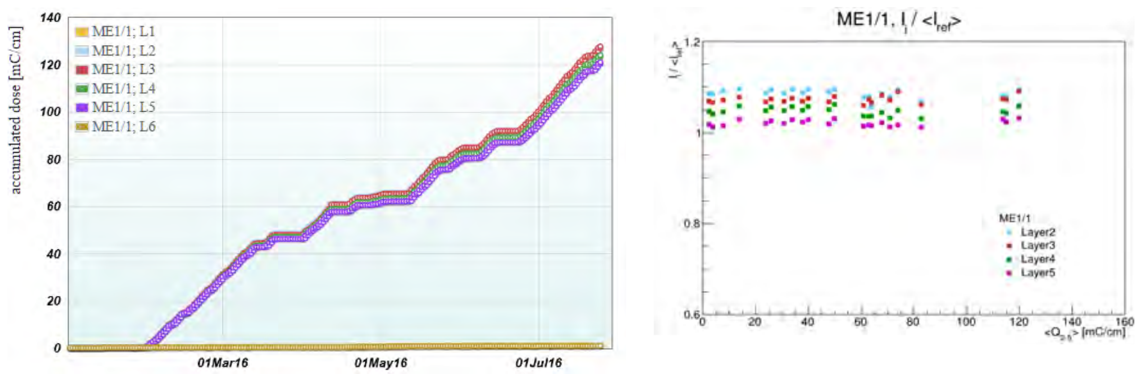


Figure 20. Left: accumulated charge per unit wire length (in C/cm) as a function of time (Feb-Jul 2016). Right: gas gain stability as a function of accumulated charge. The current of each irradiated layer (2-5) is normalized to that of non-irradiated layers (1,6). Measurements and analysis by UW student Long.

extreme conditions. Dr. Lanaro and Prof. Herndon will involve UW group members in these studies. In early 2018 we expect to complete the present aging campaign at GIF++ which should qualify the CSC for 10 years of operation at the HL-LHC

4.2.3 EMU Plans for Consolidation and Upgrade for HL-LHC

For the HL-LHC, the EMU detectors will be 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. Student Taylor has performed simulations to quantify the impact on performance of a degraded system, for some relevant channels (e.g. $H \rightarrow 4\mu$), motivating the upgrade. The refurbishment of the on-chamber electronics will take place during LS2, beginning in early 2019. This is a large effort and has required significant planning by Senior Scientist Lanaro along with CMS techncial Coordination since since it requires chamber removal and re-installation. The UW team at CERN work on chamber removal, refurbishment, testing, installation and re-commissioning in CMS, for the estimated ~1 year duration (2019-2020) of the project. The DAQ upgrade will be done in LS3. As Project Manager Dr. Lanaro edited the 2015 CMS HL-LHC Technical Proposal and is preparing the Muon System Upgrade TDR, planned for the fall of 2017.

Dr. Lanaro along with Dr. Savin and Prof. Herndon in their roles in the HL-LHC upgrade physics studies group, are all contributing to defining the best strategy for enhancing the capability of the overall forward muon system (triggering, redundancy and coverage extension) for improving Higgs sector measurements, detecting rare processes and searches for new physics in final states with multiple muons.

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. 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 is conducted using direct NSF support, most recently through their Physics at Information Frontier program "Any Data, Any Time, Any Where" (AAA) grant.

The 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 8800-jobslot computing cluster providing 85500 HS06 units and 4.9-PB (raw) high-availability distributed storage service. 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 US Open Science Grid (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.

Our Tier-2 facility serves as the primary analysis computing 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., 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 prompt analysis of 2015 data, followed immediately by ICHEP work using recently acquired 2016 data. This work resulted in several 13-TeV 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. UW Tier-2 achievements are compared to other sites in . Close collaboration of Task T physicists with the NSF-supported computing team results in above average productivity.

Table 1. UW Tier-2 achievements compared to others for Aug. 1, 2015 to July 31, 2016.

Activity	Wisconsin T2	US OSG T2s <Avg>	All CMS T2s (57)
MC Events Produced	5.5 B	23.4 B <2.9 B>	61.1 B
Events Reprocessed	2.0 B	13.4 B <1.7 B>	28.7 B
Events Analyzed (users)	295 B	1.37 T <171 B>	2.74 T
Data Hosted	1.3 PB	10 PB <1.4 PB>	~25 PB
Data served on WAN by AAA	7.9 PB	20 PB <2.4 PB>	31 PB

6 Activities of UW CMS Faculty

6.1 Professor Wesley Smith

In 2014-16, Prof. Smith supervised 3 students (in addition to 5 students in 2011-13 and 4 present students) who have graduated with CMS theses. They are Isobel Ojalvo on the W+bb cross section and a MSSM $H \rightarrow \tau\tau$ + bb search, Austin Belknap on the spin and parity of the Higgs Boson in the $H \rightarrow ZZ \rightarrow$ 4l channel and a search for a doubly charged Higgs and Tom Perry on W+bb production and a search for mono-photon signals of dark matter. Over his career, Prof. Smith has had 30 of his own students receive a Ph. D. in particle physics. Some of those continuing in particle physics have become tenured faculty, including Prof. Anna Goussiou at U. Washington and Prof. Sabine Lammers at U. Indiana.

Prof. Smith's physics studies for the next 3 years concentrate on understanding the characteristics of the Higgs boson, particularly decays to τ's, searches for MSSM Higgs and exotic Higgs and searches for DM. Jointly with Prof. Dasu he is supervising Senior Scientist Savin and postdocs Caillol and Gomber on these studies. Prof. Smith is presently supervising 4 students in their CMS physics analysis, including Laura Dodd on Higgs decays to τ's, searches for MSSM Higgs and exotic Higgs, Nate Woods on ZZ cross sections and high mass ZZ resonances decaying to 4 leptons, Nick Smith on dilepton plus missing transverse energy signals measuring $Z\nu\nu$ and invisible Higgs production and searching for Dark Matter and Usama Hussain on mono-pencil jets searches for a light Z' and Dark Matter. Prof. Smith also helped with supervision of graduated student Aaron Levine advised by Prof. Dasu on a search for lepton flavor violating Higgs decays and W production. Prof. Smith is presently assisting Prof. Dasu in the supervision of students Davin Taylor on a doubly charged Higgs search and WZ production measurement, Tyler

Ruggles on Higgs τ's, searches for MSSM Higgs and exotic Higgs and James Buchanan on a mono-photon DM search.

Prof. Smith served as Trigger Coordinator from 2007 to July 2012 with responsibility for the CMS event selection from detector to disk through the Level-1 and Higher Level Triggers, including the selection of all the data used for the Higgs boson discovery. He was the CMS Trigger Project Manager from 1994 until the operations phase began in 2007, with responsibility for design, construction, installation and commissioning of the L1 trigger. He served on the CMS Executive and Management Boards for 18 years.

From 2012-15, Prof. Smith co-convened of the CMS Trigger Performance and Strategy Working Group that developed the trigger architecture for the CMS HL-LHC upgrade and he co-edited the trigger chapter of the CMS Phase 2 (HL-LHC) Upgrade Technical Proposal and presented this proposal for approval by the collaboration and the LHCC. From 2013-16, Prof. Smith was the US CMS Phase 1 Trigger Upgrade Project Manager, which included upgrades of the Calorimeter Layer 1 and Endcap Muon Trigger systems, which were both successfully delivered in 2015-16 and are now triggering CMS with capabilities to handle the higher luminosity. Prof. Smith continues serving as US CMS Trigger Project Manager since 1997, with responsibility for the US CMS trigger operations for the calorimeter, muon and higher level triggers with a record of high trigger performance and negligible system downtime. From 2016 onward, Prof. Smith has been the US CMS HL-LHC Calorimeter Trigger Upgrade Project Manager. Along with Prof. Dasu, Prof. Smith supervises Scientist Pamela Klabbers, the postdocs and students and the UW US-CMS project-supported team of Electrical Engineer Tom Gorski, Firmware Engineers Ales Svetek and Marcelo Vicente, Software Engineer Jes Tikalsky and Technician Bob Fobes on the UW trigger projects, including the Phase-1 Upgrade Calorimeter Trigger operations and the HL-LHC Calorimeter and Correlator L1 Trigger R&D.

Prof. Smith singly authored a review article in 2016 on Triggering at the LHC [33] and gave Trigger and Data Acquisition summer school lectures at both the CERN-Fermilab Hadron Collider Summer School and SLAC Summer Institute in 2016. He is a member of the DPF Coordinating Panel for Advanced Detectors (CPAD) and was co-Chair of the ECFA HL-LHC Preparatory Group on Trigger, Offline, Online and Computing in 2013 and 2014. He is a founding member of the organizing committee of the yearly Topical Workshop on Electronics for Particle Physics (TWEPP) that started as the Conference on Electronics for LHC Experiments in 1995. In the past year he has served on the DOE National Laboratory Energy Frontier Program Review and the DOE Comparative Review of HEP-supported National Laboratory Detector Research and Development.

6.2 Joint Activities of Prof. Dasu and Prof. Smith

Profs. Dasu and Smith jointly supervise Senior Scientist Pam Klabbers on the Level-1 calorimeter trigger, in her role as the Deputy Trigger Technical Coordinator, on analysis of its performance and upgrade, Senior Scientist Savin on SM and Higgs physics analyses, and on designs, software and analysis of the calorimeter trigger upgrade for the HL-LHC, Postdoc Bhawna Gomber on dark matter searches, SM measurements, high level trigger for Exotica physics and the Level-1 calorimeter trigger, including operations and offline software, and Postdoc Cecile Caillol on Higgs analyses, tau reconstruction and identification and the Level-1 calorimeter trigger, including operations, online software and upgrade studies for the HL-LHC.

6.3 Professor Sridhara Dasu

Prof. Dasu is involved in physics analysis, trigger operations and upgrade, and computing operations and research. Much of the activity is in close collaboration with Prof. Smith, Scientists Klabbers and Savin, postdocs Caillol and Gomber, and the graduate students of Profs. Dasu and Smith. Current graduate students directly supervised by Dasu are Buchanan, Ruggles and Taylor. He also assists Prof. Smith in the supervision of graduate students Dodd, Hussain, Smith and Woods.

Prof. Dasu served as the US CMS Collaboration Chair from July 2014 through June 2016. He organized and chaired selection committees for the new US CMS management team, ensured that US

CMS scientists are well represented in CMS wide management structure and helped form US CMS consensus behind CMS upgrades for the HL-LHC. He ensured broad representation of minority groups in the CMS management, participation of young members in the two USCMS annual meetings he chaired, and also helped the election of another US member as the new CMS spokesperson.

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. The rediscovery of the Higgs boson in 4-lepton channel using early 13-TeV data this summer with graduate student Woods (Advisor Smith) begins the Run2 program to determine its 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. Graduate students Bachtis (Ph.D. 2012, now Asst. Prof. at UCLA), Swanson (Ph.D. 2013, Advisor Smith), Ojalvo (Ph.D. 2014, Advisor Smith) had obtained their degrees developing tau trigger, reconstruction algorithms and the final analysis along with the then postdocs in the group. Currently Prof. Dasu is supervising the work of graduate student Dodd and Ruggles with postdoc Caillol and Prof. Smith, to firmly establish the H(125) coupling to tau-leptons. He is also exploring the MSSM, nMSSM and potential portal to dark matter using tau-pair analyses, with this subgroup.

Prof. Dasu searched for lepton flavor violating Higgs decays with graduate student Levine (Ph.D. 2016) using Run1 data, where slight excess was found, and 2015 data, where the excess was belied. This work will continue with postdoc Caillol using Run2 data. Prof. Dasu also searched for exotic doubly charged Higgs boson in Run1 with graduate students Belknap (Ph.D. 2014, Advisor Smith) and his advisee Taylor. An update using Run2 13-TeV data is currently underway as part of Taylor's thesis.

Prof. Dasu initiated the Wisconsin dark matter search effort with postdoc Gomber using mono-photon, mono-Z, mono-H and mono-Z' events accompanied by large missing transverse energy. With graduate student Buchanan initial searches with mono-photon channel were completed in time for 2016 conferences. With postdoc Gomber and graduate student Smith (Advisor Smith) initial searches using mono-Z channel were completed in time for 2016 conferences, with the exploration continuing using larger datasets as they accumulate. With postdoc Gomber and graduate student Dodd (Advisor Smith) a new search for mono-H, in the channel where a tau-pair recoils from dark matter, is being pursued. With postdoc Gomber, graduate student Hussain (Advisor Smith) and Prof. Bai, a search for a light Z' boson, which recoils from dark matter particles, has been initiated.

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 $W\gamma/Z\gamma$ 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 $Z(ll)Z(\nu\nu)$ and $Z(\nu\nu)\gamma$, as part of the dark matter searches, with postdoc Gomber and students Smith and Buchanan. With graduate student Taylor he is 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 and Ojalvo, and are currently studied with Scientist Klabbers, Postdoc Gomber and students Levine, Ruggles, Perry, Woods and Dodd. He helps Prof. Smith in the supervision of the UW trigger engineering team (Gorski, Svetek, Vicente, Tikalsky and Fobes).

Prof. Dasu supervises the work of Drs. Mohapatra and Vuosalo as the PI of the NSF and USCMS research program supported computing projects, including one of the largest CMS Tier-2 computing facilities and the recently completed "Any Data, Any Time, Any Where" computing research endeavor.

The ambitious future physics program outlined 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. On the grid-computing front, the scaling of operations to a million parallel processes is looming. Pleasantly, the wide area network bandwidth has become comparable to the local disk IO bandwidth. Following the AAA (Any data Anywhere Anytime) project lead, 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.

6.4 Professor Matthew Herndon

Prof. Herndon's physics studies concentrate on multiboson production and understanding the gauge structure of the standard model. He is advising graduate students Kenneth Long and was advising former graduate student William Parker (CDF), now a postdoc at the U. Maryland. He also advises postdoc Dr. Senka Duric and leads the UW effort on the CMS CSC muon project, which includes Senior scientist Dr. Armando Lanaro, Dr. Duric, Mr. Long and graduate student Devin Taylor (Advisor Dasu).

Dr. Parker completed his Ph.D. Thesis on the subject of Higgs boson searches in the WW decay and WW cross-section measurements in December of 2014. The cross section analysis, published in 2015, involved a differential cross section measurement of diboson production vs. the number of jets and jet energies, which was the first of it's kind. It was an essential element in Prof. Herndon's program to measure massive vector boson scattering processes where understanding jet kinematics in di-boson production is a key issue.

On the CMS experiment Prof. Herndon, with his student Mr. Long and postdoc Dr. Duric, participated in measurement of WZ and ZZ cross sections and aTGC searches. Dr. Duric has primarily worked on aTGC searches included in the 8 TeV WZ paper and the 7 and 8 ZZ TeV papers. In close collaboration with Prof. Herndon she has also developed a framework for aTGC combinations 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 multiboson group. This work is being expanded to produce NLO QCD aTGC searches and combinations with Higgs results. Dr. Duric's extensive activities in the SMP multiboson group led to her being appointed SMP multiboson convener for 2016-1017. Mr. Long has concentrated on producing the first results in WZ and ZZ production using the 13 TeV collision data and is now turning to vector boson scattering and aQGC searches in the WZ mode using the full 2016 data set. Mr. 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. Also the WZ physics framework will be leveraged to perform a WWW search in the leptonic decay modes. In summary, this physics effort is progressing from the initial cross section measurement to differential measurements of kinematic properties of the bosons and jets, aTGC and aQGC searches, measurement of pure EWK production, which includes unique processes such as SM QGC and Higgs scattering, and, at the HL-LHC, searches for massive longitudinal vector boson scattering. Prof. Herndon also leads the SMP HL-LHC physics studies group.

On the CMS muon system Prof. Herndon works with Mr. Long, Mr. Taylor and Dr. Duric 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 participate in CSC construction and installation where the upgrade of the CSC ME4/2 chambers has been completed and operated with excellent performance in 2016. Finally Dr. Duric and Mr. Long have participated in the setup and operation of a long-term longevity test stand for the CSC muon chambers at the GIF++ facility. This stand is being used to test the instantaneous and integrated radiation tolerance of the CSC chambers under HL-LHC radiation conditions. Mr. Long continues to participate in the project operating the test stand and analyzing data.

During this time period Prof. Herndon engaged in two other major activities outside of the scope of the CMS experiment. In the spring and summer of 2014 in collaboration with the Fermilab computing division he designed programing workshop course entitled "FNAL Programming Reconstruction Software for Large Computing Projects". This course was designed to teach students programming techniques in C++ for programing effectively in a large scale computing project. The course used the example of a toy tracking detector and associated code. The students studied and solved various computing problems in tracking within that framework. Prof. Herndon wrote the software and course materials while on a one semester teaching buy-out sabbatical funded by Fermilab and taught the one week workshop course that summer. In the summer of 2016 Prof. Herndon chaired the organizing committee of Multiboson Boson Interactions 2016 (MBI 2016). He organized this workshop that was held in Madison at the end of 2016. This was the fourth in a highly successful set of workshops on MBI, which bring together experimentalists and theorists to discuss the subject. Prof. Herndon is one of the founding organizers and has been on the organizing committee for each workshop.

7 CMS & US CMS Management Responsibilities

CMS and US CMS management positions held by (current in 2016) 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. Smith:	Manager, US CMS Trigger Project (M&O and Phase-1 Upgrade) (Level-2)
	Manager, US CMS Calorimeter Trigger HL-LHC Upgrade Project (Level-3)
Prof. Dasu:	Manager, US CMS Calorimeter Trigger Project (Level-3)
	Member, US CMS Resource Allocation Advisory Board
Prof. Herndon:	Coordinator, SMP Future Physics and Phase 2 Studies (Level-4)
Sen. Sci. Dr. Klabbers:	CMS Deputy Trigger Technical Coordinator (Level-3)
Sen. Sci. Dr. Lanaro:	CMS Project Manager, CSC System (Level-3)
	US CMS Deputy Project Manager, EMU / CSC System (Level-3)
Sen. Sci. Dr. Savin:	Coordinator, CMS Future Standard Model Physics Analysis Group (Level-3)
SW Eng. Dr. Vuosalo:	Co-Coordinator, CMS Reconstruction Software (Level-3) (NSF Tier-2 Support)
Postdoc Dr. Duric:	Co-convener, SMP Multiboson Analysis Subgroup (Level-4)
	CSC Detector Performance Group (DPG) coordinator (Level-4)
Postdoc Dr. Gomber:	Co-convener, Exotica Trigger Subgroup (Level-4)
Postdoc Dr. Caillol:	Co-convener, Tau Object ID Subgroup (Level-4)
Postdoc Dr. Ojalvo:	Co-convener, Tau Physics Object Group (Level-3) (at Princeton Sept. 2016)

7.2 Past Positions

Prof. Smith:	CMS Trigger Coordinator (2008-12) (Level-2)
	CMS L1 Trigger Project Manager (1994-2008) (Level-2)
	Co-convener, CMS HL-LHC Trigger Working Group (2013-15) (Level-3)
	Member, CMS Executive Board (2005-12), Management Board (1994-2012)
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-3)
	Co-convener, CMS Electroweak Physics Group (2008-09) (Level-3)
	Co-convener, CMS Online Selection Group (2005-07) (Level-3)
	Co-convener, CMS Higgs2Taus Subgroup (2012-13) (Level-4)
	CMS Trigger and Data Acquisition Resource Manager (2012-14) (Level-3)
Prof. Herndon:	Co-convener, CMS SMP Multiboson Group (2012-13) (Level-4)
Sen. Sci. Dr. Lanaro:	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-3)
	Co-convener, Tau Physics Objects Group (2012-13) (Level-3)
	Co-convener, Trigger Performance Subgroup (2008-11) (Level-3)
Researcher Dr. Mohapatra:	Co-manager, CMS Worldwide Monte Carlo Production (2008-15) (Level-4) (NSF Tier-2 Support)

References for Task T

Since January 2014 Wisconsin group members have been responsible for the published papers and preliminary but public physics analyses listed below. Internal note numbers are also cited. We have also participated on over 75 Analysis Review Committees for CMS results. We have given 38 CMS talks and 5 posters at conferences on physics using LHC data, and over 750 internal CMS talks. Information on these is provided on: http://www.hep.wisc.edu/wsmith/cms/doe16/

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   Internal Notes: Based on multiple documents. UW contribution in ττ and ZZ* modes.
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8. *Public Paper*: 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, submitted to EPCJ.
   Internal Note: M. Herndon, S. Duric, Measurement of inclusive and differential WZ cross section and search for anomalous triple gauge couplings in pp collisions at sqrt(s) = 8 TeV.
9. *Public Paper*: Measurement of the WZ production cross section in pp collisions at sqrt(s) = 13 TeV, Submitted to Phys. Lett. B.
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   Internal Note: I. Ross, J. Swanson, A. Savin, S. Dasu, et al, CMS AN-2013/007
10. *Public Paper*: Measurement of W+W- and ZZ production cross sections in pp collisions at sqrt(s)=8 TeV, Phys. Lett. B 721 (2013) 190–211
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Internal Note: I. Ross, J. Swanson, A. Savin, S. Dasu, S. Djuric, et al, CMS AN-2012/107
12. *Public Paper*: 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].
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