Experimental Particle Physics Research at Texas Tech University

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Abstract

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The high energy physics group at Texas Tech University (TTU) concentrates its research efforts on the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) and on generic detector R&D for future applications. Our research programs have been continuously supported by the US Department of Energy for over two decades, and this final report summarizes our achievements during the last grant period from May 1, 2012 to March 31, 2016.

After having completed the Run 1 data analyses from the CMS detector, including the discovery of the Higgs boson in July 2012, we concentrated on commissioning the CMS hadron calorimeter (HCAL) for Run 2, performing analyses of Run 2 data, and making initial studies and plans for the second phase of upgrades in CMS. Our research has primarily focused on searches for Beyond Standard Model (BSM) physics via dijets, monophotons, and monojets. We also made significant contributions to the analyses of the semileptonic Higgs decays and Standard Model (SM) measurements in Run 1. Our work on the operations of the CMS detector, especially the performance monitoring of the HCAL in Run 1, was indispensable to the experiment. Our team members, holding leadership positions in HCAL, have played key roles in the R&D, construction, and commissioning of these detectors in the last decade. We also maintained an active program in jet studies that builds on our expertise in calorimetry and algorithm development. In Run 2, we extended some of our analyses at 8 TeV to 13 TeV, and we also started to investigate new territory, *e.g.,* dark matter searches with unexplored signatures.

The objective of dual-readout calorimetry R&D was intended to explore (and, if possible, eliminate) the obstacles that prevent calorimetric detection of hadrons and jets with a comparable level of precision as we have grown accustomed to for electrons and photons. The initial prototype detector was successfully tested at the SPS/CERN in 2003-2004 and evolved over the last decade. In 2012-2015, several other prototypes were built to further reduce leakage fluctuations, improve Cherenkov light yield, increase fiber attenuation length, and other related phenomena.

During this grant period, we graduated two students with Ph.D. degrees, and five undergraduate students from our labs went on to prestigious graduate programs in the US and Europe. Also, the TTU HEP team has participated in the QuarkNet program every year since 2001. We are dedicated to working with area teachers and students at all levels and to training the next generation of scientists. Over 20 high school teachers have participated in our program since its inception.

Chapter 1

Introduction

TTU's focus has always been on collider experiments at the highest energies, including significant efforts in detector research and development to support advancements in particle physics. During this grant period, we focused on CMS data analyses from Runs 1 and 2 at the LHC, on commissioning and operation of the CMS detector for Run 2, on Phase 2 upgrades, and on dual-readout calorimetry R&D. Our usual grant covered the first three years (May 1, 2012 to March 31, 2015) with Richard Wigmans as the lead PI, and the fourth year (April 1, 2015 to March 31, 2016) was supplemental with Nural Akchurin as the lead PI. There was no detector R&D component for the last (fourth) year. The TTU HEP team consisted of four faculty (Nural Akchurin, Sung-Won Lee, Igor Volobouev, and Richard Wigmans), four postdoctoral fellows (Christopher Cowden, Jordan Damgov, Cosmin Dragoiu, and Phillip Dudero), nine graduate students at various stages of their careers (James Faulkner, Keng Kovitanggoon, Kamal Lamichhane, Terence Libeiro, Tielige Mengke, Samila Muthumuni, Sonaina Undleeb, Zhixing (Tyler) Wang, and Zhen Xu), and several undergraduate students. Lee took faculty development leave in Fall 2013, and Volobouev completed his stay at Fermilab's Large Hadron Collider Physics Center (LPC) on a Universities Research Association (URA) fellowship and faculty development leave in Fall 2014 and Spring 2015.

The last four years witnessed several major accomplishments by our group members. Terence Libeiro, advised by Igor Volobouev, completed his Ph.D. thesis (*Measurement of Inclusive Jet Production at* $\sqrt{s}$ *=2.76 TeV with the CMS Detector and Calibration of FFTJet Algorithm*) in May 2015. Keng Kovitanggoon, advised by Sung-Won Lee, finished his Ph.D. studies (*Study of Jets Production in Association with W and Z Boson in pp Collisions at* $\sqrt{s} = 7$ *TeV*) and graduated in May 2014. He joined Chulalongkorn University in his native Thailand as a postdoc and continues to work on the CMS experiment.

Dudero was awarded the distinguished URA-FNAL Visiting Scholars Fellowship, by the University Research Association, a 50% salary support fellowship in 2014. His project was titled *Study of SM and BSM Processes in the Decay Chain* $W+X \rightarrow \ell+\nu+$ *jets.* Dudero was also elected a 2015 Junior CMS LPC Distinguished Researcher in recognition of his analysis work on dibosons.

Our undergraduate students also did well. Jonathan Clark, who graduated *magna cum laude* in May 2014, is attending graduate school at UT-Austin on a prestigious fellowship. John Sandy, who worked on Z' searches in CMS for his honors thesis, started his graduate program in physics at UC-Irvine in 2015. John Hefele plans to attend University of Leiden for his graduate studies in physics this year.

The HCAL has traditionally been the focal point for our group. The HCAL Calibration group was led by Akchurin and Damgov for the last several years. Dragoiu assisted Damgov in the calibration of the forward detectors. Volobouev has been working on jet energy calibration and HCAL event reconstruction, including pileup mitigation. He also been serving on the CMS Statistics Committee. Cowden developed the HCAL online/offline Data Quality Monitoring (DQM). Our graduate students started monitoring HCAL status at our "Remote Operations Center" (ROC) and have been regularly reporting to the operations group at CERN. Lee, in addition to serving on the CMS Conference Committee, was a co-convener of Standard Model Jet physics and Exotica Multijet groups in Run 1.

TTU group developed a new type of a combined (electromagnetic plus hadronic) compensating and Compact Forward Calorimeter (the CFC option) proposal to replace the existing CMS endcap calorimeters with a unified fiber calorimeter in Phase 2. The CFC proposal, inspired by the dual-readout technique, was developed over the course of a year and contained several novel ideas, such as event-by-event compensation, excellent jet energy resolution, and pileup mitigation by Cherenkov pulse timing. Although in April 2014 our proposal was turned down, one positive outcome was the forming of an international generic R&D collaboration on the production and evaluation of rare earth-doped silica radiation-hard fibers (*e.g.* SiO_2:Ce^{3+}, DBS:Ce^{3+}, SiO_2:Pr^{3+}).

Our group hosted the XVth International Conference on Calorimetry in High Energy Physics (CALOR 2012) in June 2012 in Santa Fe, NM [1]. We were pleased to organize a major international conference in our area of expertise and to discuss the role of calorimetry in Higgs searches one month before the Higgs boson discovery announcement in July 2012.

This report is organized by task: TTU's contributions to CMS is described in Chapter 2 (The Energy Frontier - Task A), and our generic detector R&D work in dual-readout calorimeters is presented in Chapter 3 (The Detector R&D - Task B). In Appendix A, we list our publications and analyses notes with significant contribution from our group members along with a list of major conference presentations at the end of this report for both tasks combined.

Chapter 2
CMS - The Energy Frontier (Task A)

We give short descriptions of CMS activities in 2012-2016 in this chapter. Physics analyses (Section 2.1), physics objects (Section 2.2), detector performance (Section 2.3), and the upgrade activities (Section 2.4) are grouped into four sections.

Our postdocs performed at the highest level and were appreciated by the CMS collaboration. Cowden, before he left our group for an IT position in Dallas in 2015, focused on the HCAL noise monitoring and diagnostics. His physics analyses centered around the background suppression in the dark matter searches and the Dirac monopole search from Run 1. Damgov, an expert in MET, served as the JetMET DQM convener and led the diboson search analysis after completing his tenure in the HCAL Calibration group. Dragoiu completed the HF electron ID development and the Z/γ forward-backward asymmetry (A_{FB}) measurement at $\sqrt{s} = 8$ TeV. He also left for a position in industry in 2015. Dudero took on the simulations of the high granularity calorimeter (HGC) for the test beam and CMS configurations, and also led the analyses of dibosons at $\sqrt{s} = 13$ TeV. Akchurin was responsible for the Phase 2 upgrades and contributed to the dark matter (DM) search analyses; Lee was in charge of the dijet and diboson analyses; and Volobouev headed all work in jet and HCAL energy reconstruction, including pileup.

Starting 2016, we hired three new postdocs. Emine Gürpinar, a Çukurova University Ph.D., will be working on DM searches with monojets and HCAL. Federico De Guio, a recent CERN fellow, will be working on HCAL DQM development for Run 2 and dijets. Timo Peltola, a recent Ph.D. from the Helsinki Institute of Physics, is an expert in silicon sensor simulations and will concentrate on the HGC project.

2.1 Physics Analyses

We present some of the highlights of our analyses results below. We think that these results would not have been possible without the crucial contributions of our group members.

2.1.1 Search for Dijet Resonances

In 2010, the CMS dijet analysis group, co-led by Lee, performed a search for narrow resonances in the dijet mass spectrum using 2.9 pb^{-1} of data. This analysis resulted in the first CMS search publication [2]. As no evidence for new particles was found, we presented upper limits at 95% CL on the product of the resonance cross section, branching fraction, and acceptance ($\sigma \times BR \times A$) separately for decays into quark-quark, quark-gluon, or gluon-gluon pairs. We also set specific mass limits on string resonances, excited quarks, axigluons, colorons, and E_6 diquarks, all of which extended previous exclusions. Multiple updates to dijet resonance analysis [3–7] were published as the integrated luminosity increased. In 2011-2013, our analysis incorporated particle-flow (PF) jets reconstructed with the anti-k_T algorithm into "wide jets" in order to reduce the effect of gluon radiation on the dijet mass resolution.

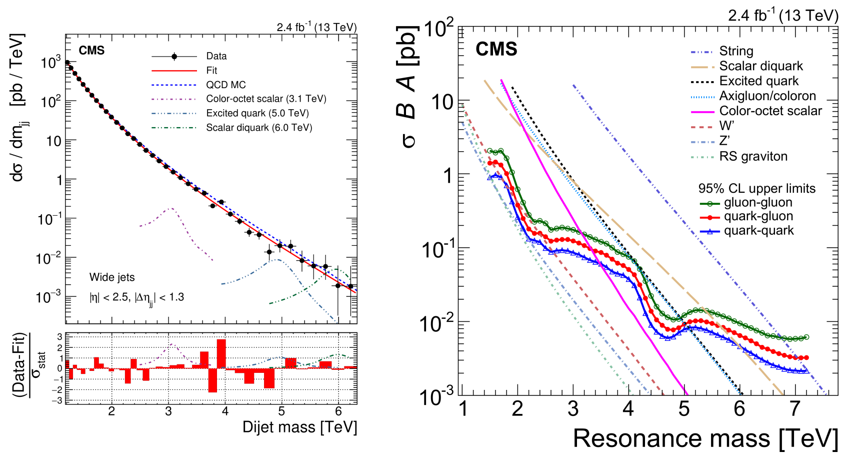
In 2015, in collaboration with the CMS dijet group, we performed a search for narrow resonances in the diet mass spectrum at $\sqrt{s}$ = 13 TeV. The 2.4 fb^{-1} of data used in this search were collected during the Run 2. Figure 2.1.a shows the dijet mass distribution for the inclusive sample, with bins approximately equal to the dijet mass resolution. The data are well described by the fit and no significant deviation from

Table 2.1: The summary of the analysis activities by the TTU HEP group in CMS for the grant period 2012-2016. Our Ph.D. recipients are indicated by a dagger (†).

Run 1 Analyses				
Topic	Personnel	Year	Pubs	Main Collaborators
Searches with Dijets	Akchurin, Gümüş† Lee, Jeong† Kunori, Lee	2008 2009-2012 2013-2015	[8,9] [2–4,10] [5,6]	FNAL CERN, FNAL CERN, FNAL
Searches with Monophotons Searches with Monojets	Akchurin, Damgov, Lee Kunori	2011-2012 2010-2014	[12] [13–15]	FSU, KSU, Davis Cukurova (TR), Imperial, RAL, TAMU
Higgs ($WW \to \ell\nu jj$)	Damgov, Dudero	2010-2015	[23,24]	CERN, FNAL
Diboson and aTGC/aQGC	Lee, Damgov, Dudero, Faulkner	2011-2015	[26,29]	FNAL, TAMU
Monopole Search	Akchurin, Lee, Cowden	2012-2015		Davis
Z+1 jet angular Z+Jets cross sections Jet cross section	Lee, Kovitanggoon† Lee, Kovitanggoon Lee, Volobouev, Libeiro†	2010-2014 2013-2015 2013-2015	[31,35] [36,37] [41]	FIU, NCU (TW) ULB (BE), METU (TR) KIT (DE), Tata, Helsinki
A_{FB} ($e^+e^-, \mu^+\mu^-$) 7 TeV A_{FB} (e^+e^-) 8 TeV	Akchurin, Roh† Akchurin, Lee, Dragoiu, Sandy	2008-2011 2012-2015	[38,39] [40]	FNAL, Rochester JINR, Rochester
Run 2 Analyses				
Topic	Personnel	Year	Pubs	Main Collaborators
DM Searches with Dijets	Kunori, Lee, Dragoiu, Wang	2015-	[45]	Athens, FNAL, Rome, Rutgers
DM Searches with MonoX	Akchurin, Kunori, Cowden, Undleeb, Lamichane, Muthumuni	2015-	[46,47]	Cukurova (TR), TAMU, UNESP (BR) UCSD
Multiboson + Jets Physics (Heavy Higgs/Resonances, EWK and aTGC/aQGC)	Lee, Volobouev Damgov, Dudero, Faulkner, Xu	2015-	[48–50]	CERN, FNAL, Milano, Peking, Zurich

the background hypothesis is observed. For comparison, we also display the shape expected three signal models. New particles are excluded at the 95% CL in the mass regions for which the theoretical curve lies above observed upper limit for the appropriate pair of partons (Figure. 2.1.b). We have also determined the expected lower limit on the mass of each new particle by comparing the expected cross section limits to the model predictions. These results significantly extend previously published limits [6]. The main results of this analysis using Run 2 dataset have been published in PRL [45].

The TTU group has been involved in CMS dijet physics since 2005. Originally, dijet search sensitivity was estimated and the first analysis tools were developed by Kazim Gümüş for his Ph.D. thesis [8, 9]. Following his graduation in 2008, another TTU graduate student, Chiyoung Jeong, improved the analysis as a part of his Ph.D. research [10], creating the basis for CMS publications mentioned above [2–4]. Following Chiyoung's graduation in 2011, the analysis toolkit was handed over to a group of new students at the Fermilab LPC, and they completed an update [6]. The analysis results from 42 pb^{-1} of data at $\sqrt{s} = 13$ TeV were shown at the LHCP Conference in September 2015. DM searches using dijets is Zhixing (Tyler) Wang's thesis topic.



(a) (b)

Figure 2.1: (a) Dijet mass spectrum from wide jets (points) compared to a smooth fit (solid line) and to predictions including detector simulation of QCD and signal resonances. The highest mass dijet event is observed at 6.1 TeV. The bin-by-bin fit residuals normalized to the statistical uncertainty of the data, (data-fit)/σ_{data}, are shown at the bottom. (b) The observed 95% CL upper limits on $\sigma \times \text{BR} \times \text{A}$ for dijet resonances of the type gluon-gluon, quark-gluon, and quark-quark, compared to theoretical predictions for various models [6].

2.1.2 Search for Dark Matter with MonoX

Akchurin, Damgov, and Lee performed a search for DM and large extra dimensions (LED) in 5 fb^{-1} of 2011 data [12]. Seventy-three candidate events passed the analysis selection criteria; thus, they are consistent with the expected background of 75.1 ± 9.5. This null result was interpreted as a limit on the DM production cross section and then translated into the DM-nucleon scattering cross section. Limits on the Arkani-Hamed, Dimopoulos, and Dvali (ADD) extra dimensions [11] were also established.

CMS searches for new physics in the jet + $\not{E}_{\text{T}}$ channel, co-led by Kunori, resulted in three publications: over 36 pb^{-1} integrated luminosity of 7 TeV data [13], 5 fb^{-1} of 7 TeV data [14], and the full 20 fb^{-1} of 8 TeV data [15]. During the 8 TeV run in 2012, monojet events were collected using the $\not{E}_{\text{T}}$ trigger customized for the monojet analysis. We observed no excess over the expected SM backgrounds. Using this measurement, limits on the non-SM contribution to events passing the event selection were set at 95% CL. These limits were then translated to the limits on DM, ADD, and unparticles [16, 17].

Figure 2.2 shows the limits on the DM-nucleon scattering cross section from the monophoton and monojet analyses together with projections for 300 and 3,000 fb^{-1} at 14 TeV. Our results led to the world's most stringent limits below $M_\chi = 4$ GeV in the spin-independent case and below 400 GeV in the spin-dependent case. In Run 2, these limits will be improved by at least an order of magnitude.

We extended our Run 1 monojet analysis to test new models. Sonaina Undleeb tested the light non-thermal DM model [19] using the 8 TeV data and obtained similar bounds (Figure 2.3.b). This model explains both the baryon abundance and the estimated DM content of the universe. The diagram $dd' \to X^* \to \bar{u}\ n_{DM}$ describes monojet production and $dd' \to X^* \to \bar{t}\ n_{DM}$ describes monotop (top diagram in Figure 2.3.a) when χ^* decays into a DM particle and an antiquark. Two-body decays of the heavy mediator X^* create a Jacobian peak in the $\not{E}_{\text{T}}$ distribution. We extend the legacy monojet analysis to look for the Jacobian peak and also to include three-jet events for monotop. This is the first analysis to look for a bump in the $\not{E}_{\text{T}}$ distribution in DM searches.

The $\not{E}_{\text{T}}$ distribution from Undleeb's analysis of the LHC Run 2 data is shown in Figure 2.3.c. We observed 23 events in the 400 GeV $< \not{E}_{\text{T}} <$ 600 GeV range with the 42 pb^{-1} sample, with estimated background of 26 [46, 47]. We expect the sensitivity of the search to reach $\lambda_1 = \lambda_2 = 0.05$ with 100 fb^{-1}

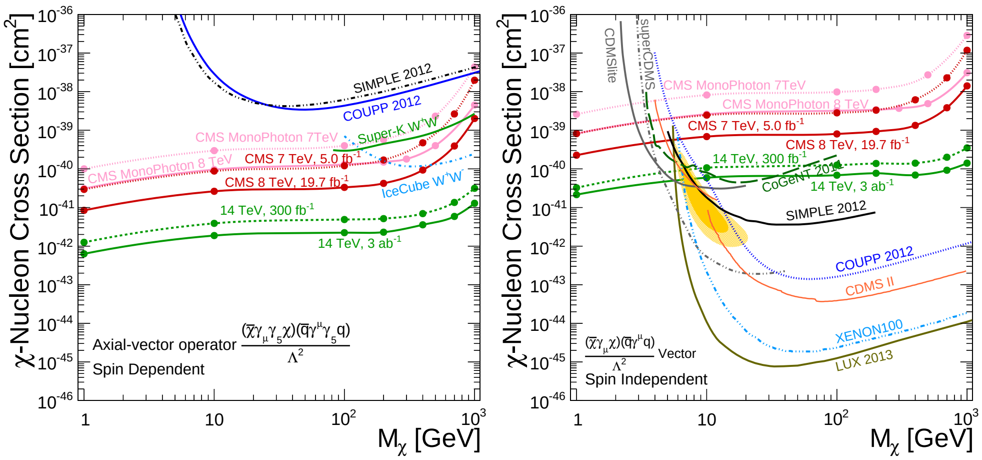
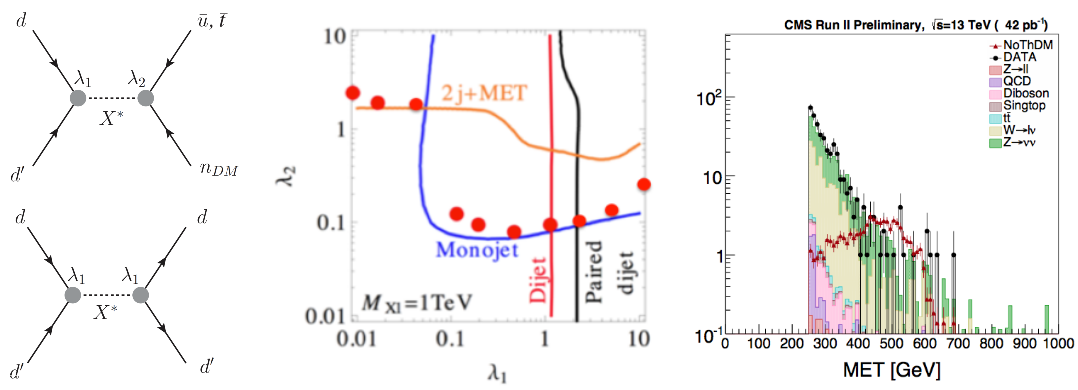


Figure 2.2: Projection of 90% CL spin-dependent and spin-independent limits for the DM-nucleon scattering cross section as a function of DM particle mass with 300 fb^{-1} and 3 ab^{-1} at 14 TeV [18]. Also shown are the previously published results by the TTU group [12, 14, 15].

of data. This analysis is also applicable to other models that produce a bump in the $\not\!\!E_T$ distribution, such as the Fermion Portal DM production [20].

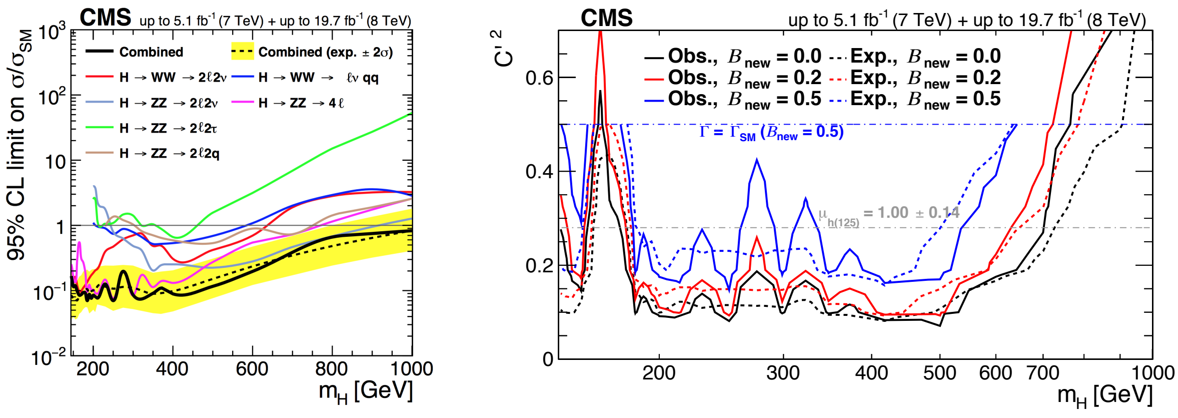


(a) (b) (c)

Figure 2.3: (a) The two most important diagrams in the light non-thermal DM model that lead to monojet (top) and dijet (bottom) production. n_{DM} is the light DM in the model, and d and d' are down quarks and u is up quark. In the heavy M_{X^*} limit, $\sigma \propto |\lambda_1|^2|\lambda_2|^2/(2|\lambda_1|^2+|\lambda_2|^2)$ for monojet and $\sigma \propto |\lambda_1|^2$ for dijet. (b) Limit plot in the $\lambda_1-\lambda_2$ plane from [19]. Filled circles are preliminary results from Sonaina Undleeb using 8 TeV data and the Run 1 CMS monojet analysis framework. (c) The $\not\!\!E_T$ distribution from Undleeb's analysis using 13 TeV data and the new Run 2 analysis framework. The monojet event selection criteria inherited from Run 1 analysis were applied. The non-thermal DM signal was simulated for the mediator mass of 1 TeV, DM mass of 0.938 GeV, and the coupling constants $\lambda_1 = \lambda_2 = 0.5$.

2.1.3 Search for Higgs-like Resonances Decaying into the WW Final State

A major thrust of the CMS collaboration over the last couple of years has been to finalize the legacy physics analyses using the Run 1 data that consists of 5 fb^{-1} at 7 TeV collected in 2011 and 20 fb^{-1} at 8 TeV in 2012. This objective applies to all studies of the Higgs boson discovered at 125 GeV [21, 22], as well as to searches for additional Higgs bosons with higher masses. In the latter category, a combination paper from several high mass searches has been approved by the CMS collaboration. Dudero and Damgov, in collaboration with the LPC members at Fermilab, made decisive contributions to this



(a) (b)

Figure 2.4: (a) The improved combined limit using all 7 TeV and 8 TeV data: the observed limits of the combined and six individual channels are shown. (b) Upper limits on the heavy EWK singlet model parameter C'^2 are displayed as a function of the heavy Higgs boson mass for different values of B_{new}. The upper dash-dotted line indicates where, for $B_{\mathrm{new}} = 0.5$, the variable width of the heavy Higgs boson reaches the width of a SM-like Higgs boson. The lower dash-dotted line displays the indirect limit at 95% CL on C'^2 from the measurement of the discovered Higgs boson. All participating channels are combined [24].

paper. Since 2010, we have been focusing on the Higgs decay to WW, followed by the decay of one of the W bosons to a lepton-neutrino pair, and the other to two resolved jets or a single merged jet in the case of a significantly boosted boson (the so-called "semileptonic" channel).

The 2013 paper [23] on the search for a heavy SM-like Higgs (m_{H} =140 to 1,000 GeV) covered all channels that proceed through the decay of two W or two Z bosons. The dataset included all of the 2011 data and a part of the 2012 data (5 fb^{-1} at 8 TeV). One of the key plots from this paper was chosen for the cover of the European Physics Journal C, June 2013 issue. The analysis was presented by Dudero at the Hadron Collider Physics Symposium in Kyoto, Japan in 2012. The improved analysis result that combines all of the 7 and 8 TeV data is shown in Figure 2.4.a. The combined upper limits at the 95% CL on the product of the cross section and branching fractions exclude an additional Higgs boson with SM-like couplings in the full search range $145 < m_{\mathrm{H}} < 1{,}000$ GeV [24]. The results were also interpreted in a BSM Higgs scenario, based on an effective theory that predicts the existence of a heavy Higgs singlet (Figure 2.4.b).

The 125 GeV Higgs boson is consistent with the unitarity constraints on WW scattering at high energies. Nevertheless, there is still a possibility that this boson is a part of a larger Higgs sector and only partially responsible for the electroweak symmetry breaking. Several BSM scenarios, such as Higgs-doublet models, heavy EWK singlet models, or Split SUSY models, predict heavier Higgs resonances at the TeV-scale. Therefore, it is important to continue searching for Higgs bosons in the high mass region.

2.1.4 Multiboson Production, Constraints on Anomalous Triple and Quartic Gauge Couplings (aTGC and aQGC), and the Search for WW/WZ Resonances

The study of diboson pair production has long been considered crucial to understanding the electroweak symmetry breaking and the adequacy of the SM description of nature [25]. By measuring the production cross section, one gains the ability to probe the strength of boson self-interaction as predicted by gauge symmetry. A deviation from the SM prediction would indicate a presence of new physics. Such a deviation can be characterized by an anomalous boson self-coupling through a triple vertex.

In 2011, we performed a measurement of the inclusive WW+WZ diboson production cross section at

7 TeV using events containing a leptonically decaying W and two jets [26]. The measured cross section was consistent with the SM prediction. No evidence for aTGC was found, and limits on the two model parameters, λ and $\Delta\kappa_\gamma$, were set. Since the 7 TeV publication [26], we have updated this analysis using 8 TeV data with more sophisticated analysis techniques to enhance the sensitivity at high p_T [27]. The measured total cross section does not show evidence of effects beyond the SM. No evidence for aTGC is found, and limits are set on aTGC parameters. The analysis using the full 2012 dataset is complete [28], to be followed by the collaboration-wide review (CWR).

The TTU group has performed a search for $WV\gamma$ triple vector boson production that results in constraints on aQGC using events containing a W boson decaying to leptons, a second vector boson ($V = W$ or Z), and a photon. Since there is no sign of an excess above the total background predictions, it is possible to set only an upper limit on the $WW\gamma$ and $WZ\gamma$ cross sections. A limit of 311 fb was set for the inclusive cross section at 95% CL for the production of $WV\gamma$ with photon $E_T > 30$ GeV and $|\eta| < 1.44$. This limit is approximately a factor of 3.4 larger than the SM predictions that are based on NLO QCD calculations. Since no evidence of anomalous $WW\gamma\gamma$ or $WWZ\gamma$ quartic gauge boson couplings is found, we presented the first experimental limits on the dimension-8 parameter $f_{T,0}$ and the CP-conserving couplings κ_0^W and κ_C^W. The main results of this study were published in August 2014 [29].

Faulkner presented results of aTGC and aQGC analyses at the anomalous gauge couplings workshop in Dresden, Germany in October 2013. He then presented an update at the workshop for multi-boson interactions at BNL in October 2014. Damgov and Dudero gave a summary talk at the DIS conference in Dallas, TX in May 2015 and at the EPS-HEP in Vienna, Austria in July 2015, respectively, on this subject.

With 10 fb^{-1} at $\sqrt{s} = 13$ TeV, the sensitivity to heavy resonance production in diboson decay mode is significantly higher than in Run 1. Damgov gave a talk on the boosted diboson searches in CMS at the SUSY conference in Lake Tahoe (CA) in August 2015.

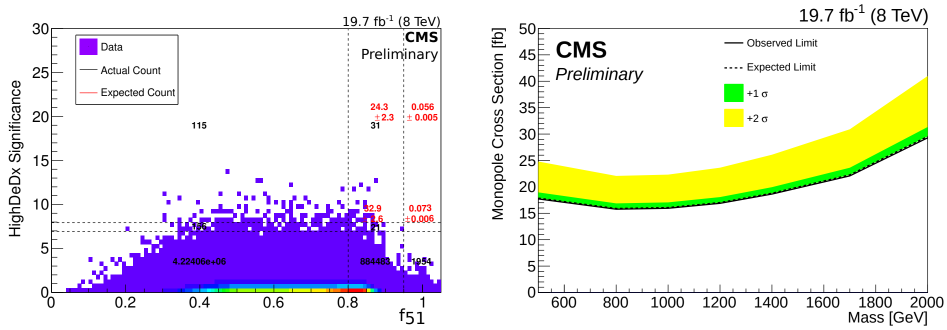
2.1.5 Run 1 Analyses

2.1.5.1 Search for Monopoles

TTU members played a leading role in the search for magnetic monopoles in CMS. Dirac's theory of magnetic monopoles leads to a quantization condition for electric and magnetic charges: $eg = \frac{1}{2}n\hbar c$ where n is any integer (or a multiple of $1/3$, depending on one's view of fundamental electric charge, e). Previous experimental work has excluded low masses of such monopoles. Therefore, one expects the monopole to have a fairly high mass (*e.g.*, ~ 1 TeV). We looked for large confined energy deposits in the ECAL, and a highly ionizing track whose trajectory curves in the r-z plane as well as the x-y plane. We developed and tested various MC production and simulation methods, and we produced large MC samples simulated with the full CMS description at TTU.

Monopoles can be effectively separated from various backgrounds by considering tracks with a large fraction of saturated hits pointing to a narrow energy deposit in the ECAL. The cluster shape in the ECAL is characterized by the fraction of energy in a narrow strip to the total energy in a cluster, f_{51}. The track hit saturation fraction significance is constructed as the probability that such a fraction of saturated tracker hits would occur from background. We employed a data driven background estimation technique to extrapolate the expected number of background events into the signal region. Figure 2.5.a shows the distribution of the track hit saturation fraction significance against the ECAL cluster discriminant f_{51}. Figure 2.5.b shows this cross-section for a number of monopole masses (500 to 2,000 GeV).

This work was accomplished by two groups: TTU and UC-Davis. While Akchurin, Cowden, and Lee worked on the energy deposition features of monopoles in ECAL (f_{51}) and ECAL noise mitigation



(a) (b)

Figure 2.5: (a) Results from the full data sample showing signal and background regions. The numbers in red are the predicted background counts in each region, and the numbers in black are the observed number of events. The horizontal axis shows the ECAL cluster discriminant f_{51}, and the vertical axis shows the track hit saturation fraction significance. (b) The observed monopole production cross-section limit assuming Drell-Yan production kinematics is competitive with previously published limits on monopole production cross section at colliders [30].

algorithms, our UC-Davis colleagues concentrated on developing track hit saturation significance parameter (dE/dx significance). The merging of the two concepts is illustrated in Figure 2.5.a. There are new groups from CERN and Egyptian institutions who are interested in this analysis for Run 2 and we transferred all our analysis framework to them.

2.1.5.2 Measurements in $Z+$Jet Events

We measured the rapidities of particles in the events containing a Z boson in association with a single jet at 7 TeV for an integrated luminosity of 5 fb^{-1} [31]. The results presented in Figure 2.6.a and b indicate that the data for the $|y_Z|$ and $|y_{jet}|$ distributions agree to better than 5% accuracy with SHERPA [32], MADGRAPH [33], and MCFM [34] QCD models over the full range of the measurement. This analysis was performed by Keng Kovitanggoon for his Ph.D. thesis [35] and is published in PRD [31]. Since the 7 TeV publication, we updated this analysis using 8 TeV data and have extended the jet rapidity acceptance to $|y|<4.7$ in order to include the HF jets. The measurements comprise inclusive jet multiplicities, exclusive jet multiplicities, and the differential cross sections as a function of jet p_T and η for the five highest p_T jets of the event [36, 37].

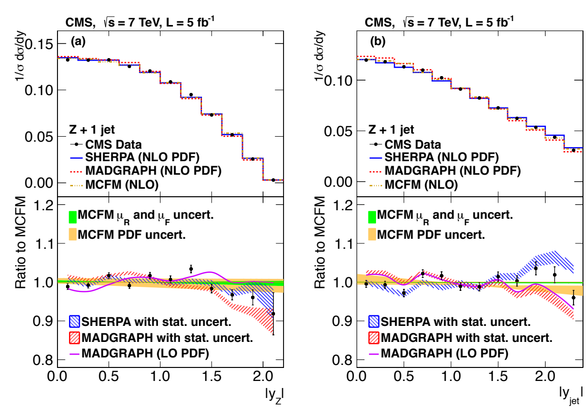
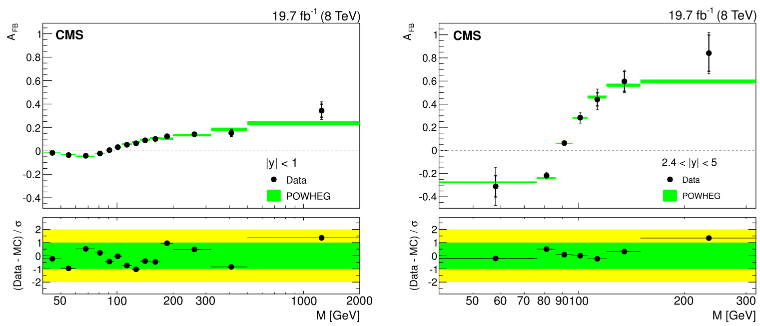


Figure 2.6: Distributions in absolute values of rapidities for the Z boson (left) and the jet (right), normalized to unity. The data are corrected for efficiency and resolution and displayed with statistical and systematic uncertainties combined in quadrature [31].

2.1.5.3 Measurement of the Forward/Backward Asymmetry (A_{FB}) in $Z \to e^+e^-$

The forward-backward asymmetries (A_{FB}) of Drell-Yan pairs at 7 TeV were previously measured by our group [38]. The muon channel was studied by then-TTU-postdoc Yazgan, and the electron channel was analyzed by Roh, who graduated with her Ph.D. degree in 2011 [39] under Akchurin's supervision. The task was transferred to Dragoiu in 2012 so that he could analyze 8 TeV data (19.7 fb^{-1}). As the asymmetry dilution effects are significantly suppressed at higher rapidities, the e^+e^- analysis was expanded to include the forward region ($2.4 < |y| < 5.0$). We developed electron identification using the HF calorimeters. The TTU team has been responsible for the conception and realization of the HF calorimeter for two decades, and it is fitting that we push the performance of the HF to its limit with this analysis.



(a) (b)

Figure 2.7: The unfolded A_{FB} measurements are indicated by black circles and the SM expectations by green bands. For example, the panel (a) gives the A_{FB} measurement in the central region ($|y| < 1.0$) while the same measurement, when one electron is in the central and the other one is required to be in the HF region, is shown in panel (b). There is a clear reduction in asymmetry dilution effects in the forward region when compared to the central region. The background estimates are subtracted from the data before unfolding. The error bars include statistical and systematic uncertainties.

Akchurin, Dragoiu, and Lee evaluated A_{FB} in five exclusive rapidity regions [40]. The A_{FB} measurement in the most central region ($|y| < 1.0$) as a function of the combined (e^+e^- and $\mu^+\mu^-$) invariant mass is shown in Figure 2.7.a. Figure 2.7.b shows the A_{FB} measurement where one central and another electron/positron that satisfied the HF electron identification criteria were selected. This analysis is now published [40].

2.1.5.4 Inclusive Jet Cross Section Measurement at $\sqrt{s} = 2.76$ TeV

As a part of his Ph.D. thesis, Terence Libeiro measured the double differential inclusive jet production cross section ($d^2\sigma/dp_{\text{T}}dy$) as a function of jet transverse momentum and rapidity with 5.4 pb^{-1} of CMS data collected in proton-proton collisions at $\sqrt{s} = 2.76$ TeV and it is recently published [41]. This measurement bridges the energy ranges studied at the Tevatron and at the LHC. It allows for improved understanding of parton distribution functions (PDFs) as well as of the running behavior of the strong coupling constant.

The reconstructed jet spectrum unfolded to the particle level is compared to the NLO perturbative QCD predictions calculated with NLOJET++ [42] using the CT10 PDF set [43] in Figure 2.8. Similar comparisons were made with a number of different PDFs and Monte Carlo generator settings. The ratio to the corresponding jet cross section measurement at $\sqrt{s} = 8$ TeV [44] has been evaluated as well.

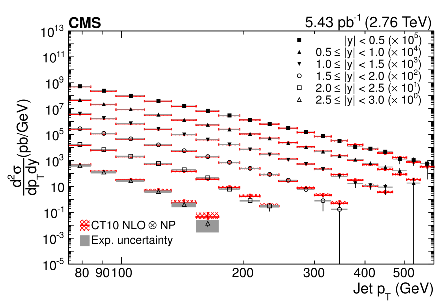
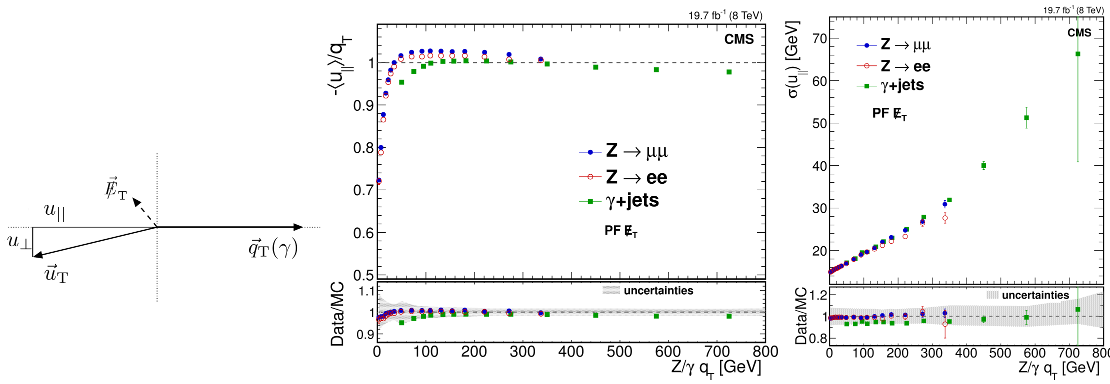


Figure 2.8: Inclusive jet cross section measured at $\sqrt{s} = 2.76$ TeV, corrected for detector acceptance and efficiency. The vertical bars indicate the statistical while the gray shaded areas represent the systematic uncertainty. The theoretical uncertainties are represented by the red hatched areas.

2.2 Physics Objects

2.2.1 Missing Transverse Energy Performance



(a) (b) (c)

Figure 2.9: (a) γ+jet event kinematics in the transverse plane. Photon momentum is $\vec{q}_T$ and the hadronic recoil, $\vec{u}_T$, is defined by the vector sum of the transverse momenta of all particles except the photon. $\vec{u}_T$ can be projected onto a unique event axis, $\hat{q_T}$, yielding two signed components, parallel ($u_{||}$) and perpendicular ($u_{\perp}$) to the event axis. (b) the response curves for PF $\not\!\!E_{\mathrm{T}}$ in events with a Z boson or direct photon. The upper frame shows the response in data; the lower frame shows the ratio of data to simulation with the gray error band displaying the systematic uncertainty of the simulation. (c) the resolution curves of the parallel recoil component versus $Z/\gamma\, q_T$ for PF $\not\!\!E_{\mathrm{T}}$.

In early Run 1, Akchurin, Damgov, and Lee made significant contributions to the commissioning of $\not\!\!E_{\mathrm{T}}$ by developing a new algorithm for $\not\!\!E_{\mathrm{T}}$ performance evaluation based on photon-jet balancing [51]. Utilizing our experience with the Run 1 data, we continued the development of $\not\!\!E_{\mathrm{T}}$ reconstruction and associated corrections for Run 2, together with performance studies at 13 TeV.

By selecting events in which a hadronic system recoils against a photon (as shown in Figure 2.9.a), the performance of the $\not\!\!E_{\mathrm{T}}$ algorithm was studied in detail, with particular emphasis on the calibration scale of the $\not\!\!E_{\mathrm{T}}$, and the resolution of the $\not\!\!E_{\mathrm{T}}$ measurement. The scalar quantity $|\langle u_{||}\rangle|/q_T$ ("$\not\!\!E_{\mathrm{T}}$ response") measures the scale factor correction required for $\not\!\!E_{\mathrm{T}}$ measurements and is closely related to jet energy scale correction and jet parton flavor. $\not\!\!E_{\mathrm{T}}$ resolution was be then assessed by measuring the RMS($u_{||}$) and RMS($u_{\perp}$). As with the response, we could examine the resolutions as functions of q_T.

The Run 1 results for the $\not\!\!E_{\mathrm{T}}$ scale and resolution using Z boson and γ+jet events are shown in Figures 2.9.b and c [52]. Figure 2.9.b illustrates the $\not\!\!E_{\mathrm{T}}$ response curves, $|\langle u_{||}\rangle|/q_T$ versus q_T, extracted from data. Deviations from unity indicate a biased hadronic recoil energy scale. The agreement between data and MC is satisfactory for each process under study. The resolution curve for the parallel recoil component, $u_{||}$, is presented in Figure 2.9.c. The data and MC curves are in reasonable agreement for each process. As the hadronic recoil is produced in the opposite direction of the Z boson or photon, $\sigma_{||}$ scales linearly with q_T while $\sigma_{\perp}$ is less impacted by the value of q_T. Taken together, Figures 2.9.b and c indicate that the measured PF $\not\!\!E_{\mathrm{T}}$ scale and resolution in data agree with the expectations from the simulation after correcting for the jet energy scale and resolution differences between data and simulation.

Since the vast majority of pileup interactions do not have significant $\not\!\!E_{\mathrm{T}}$ and the average value of $\not\!\!E_{\mathrm{T}}$ projected on any axis is zero, the effect of pileup interactions on the $\not\!\!E_{\mathrm{T}}$ response is small. However pileup has a considerable effect on the $\not\!\!E_{\mathrm{T}}$ resolution: the PF $\not\!\!E_{\mathrm{T}}$ resolution is degraded by 3.3∼3.6 GeV per pileup interaction. Therefore, pileup plays an important role in the $\not\!\!E_{\mathrm{T}}$ performance in Run 2. Evaluation of the $\not\!\!E_{\mathrm{T}}$ scale and resolution at an early stage of the Run 2 operation is an important step in commissioning of the $\not\!\!E_{\mathrm{T}}$ physics object. The TTU group will play a central role in this commissioning.

2.2.2 Validation of the CMS Jet Reconstruction Software

Since 2008, several students working with Lee have been engaged in the CMS jet validation project. The purpose of the jet validation effort is to develop a framework that checks the data for jet physics analyses in an automatic fashion and gives prompt feedback about data quality for the entire CMS analysis. We sign off on the quality of the offline release before large samples of data are (re)processed.

Our current jet validation task is divided into four areas: (a) testing improvements for the full/fast simulation packages, (2) comparing simulation results to CMS collision data as well as to MC data, (3) comparing the pile-up in full simulation with fast simulation, and (4) testing sensitivity on the choice of the parameters used by the jet clustering algorithms using QCD and $t\bar{t}$ samples with different pile-up conditions. We provided feedback to code developers on the performance of the CMS detector simulation and the validation of the new software releases using reconstructed jets. This feedback has led to better agreement for the high-p_T jet distribution when comparing fast to full simulation, for which an example is shown in Figure 2.10. In the jet validation process, we monitor about 100 different kinematic distributions like the one shown in Figure. 2.10. In Run 2, our plan is to make the feedback automatic so that we can immediately flag problems and ensure data quality for the jet physics analyses.

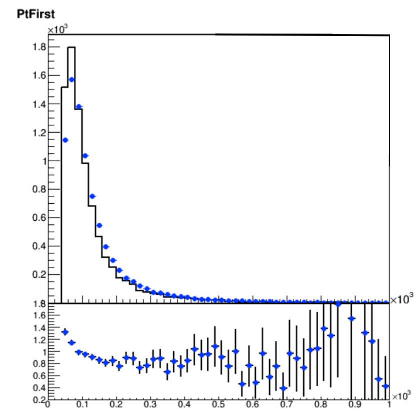


Figure 2.10: A comparison of full simulation (black histogram) and fast simulation (solid blue circles) for the leading jet p_{T} distributions using CMSSW_7_4_pre6 software release.

Before his graduation, Kovitanggoon was among those who validated updates to the jet reconstruction software. Faulkner joined in Fall 2013 and continued with this responsibility. Wang took over this task from Faulkner for Run 2. Wang is collaborating with the Jet/MET DQM group and the CERN-based physics data and MC validation team.

2.2.3 Multiresolution Energy Flow Analysis with FFTJet

FFTJet [53] is a jet reconstruction framework developed at TTU. It is aimed at building two-stage *global* jet reconstruction algorithms. In the first stage, pattern recognition is performed utilizing multiresolution filtering techniques in the Fourier domain. Jet energy determination follows, conditional upon the choice of signal topology. Description of the essential features of this approach as well as preliminary comparisons with other jet reconstruction algorithms are available elsewhere [54, 55]. In this section, we would like to point out the FFTJet features that make it especially suitable as a tool for finding boosted resonances.

In the multiresolution view of jet reconstruction, the "fat jet" and "jet substructure" concepts are no longer useful. Instead, the structure of event energy flow is analyzed using all possible η-ϕ resolution scales in some range of interest (in practice, a discrete set of scales is used with a few percent increment). Such a treatment of the event energy flow can be described by the analogy with a grayscale image. We want to view this image using different "resolution scales," as illustrated in Figure 2.11.

A very simple pattern recognition can be performed by picking the clusters found at a constant resolution scale applied across the whole η-ϕ space. Subsequently, the energy can be partitioned between jets

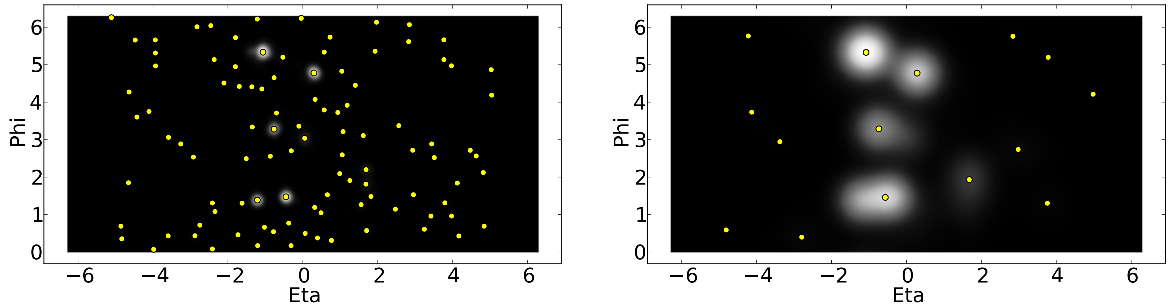


Figure 2.11: Transverse energy flow for a hadronic $t\bar{t}$ event at CMS. The pixel brightness corresponds to the amount of transverse energy deposited. The width of the Gaussian filter in the η-ϕ space is 0.1 (left) and 0.4 (right). The yellow dots indicate the positions of the local maxima found after filtering.

using, for example, K-means iteration with limited radius. This leads to something like an improved cone algorithm, with pattern recognition ambiguities eliminated [55]. However, the information contained in the transverse energy flow can be fully exploited only through a coherent analysis of all resolution scales.

In order to decompose spatial features of an image into a meaningful hierarchy of structures, one has to impose the requirement that the number of identifiable image features must decrease with increasing resolution scale. It turns out that this requirement is very strict and invariably leads to the concept of "Gaussian scale space" [56] — a representation of the event energy flow in which pattern resolution scale is associated with the width of a Gaussian filter applied to the energy flow image. After filtering, the spatial features of interest (*i.e.*, jets) manifest themselves as pixels which are brighter than their neighbors.

FFTJet connects the energy flow features found at higher resolution scales with structures visible at lower resolutions. The resulting hierarchy is called the "clustering tree" [54] (also known as the "mode tree" [57] in the statistical literature). This tree plays the role of the hierarchical clustering dendrogram supplemented by the continuous resolution scale parameter associated with every dendrogram entry. An important feature of the clustering tree is that, for each cluster, the quantity $E_{\mathrm{T}}(s) \propto s^2 m(s)$ (local transverse energy) is guaranteed not to decrease from daughter (*i.e.,* cluster at a smaller resolution scale) to parent (*i.e.,* associated cluster at a larger scale). In this formula, s is the width of the Gaussian filter and $m(s)$ is the "brightness" of the pixel.

The scale space analysis of jet configuration stability provides strong discrimination between hadronically decaying resonances and QCD jets. Distributions of two selected variables that can be used to distinguish boosted W bosons from QCD jets are shown in Figure 2.12. These distributions are results of a brief pilot simulation study (PYTHIA, particle level only, without detector simulation or pileup). Initially, both QCD jets and W bosons are generated with the same transverse momentum spectrum spanning the p_{T} range from 200 GeV to 2 TeV. Only the QCD jets which have actually been split by the algorithm into two subjets whose invariant mass is close to the mass of the W are used in these plots. Despite the invariant mass similarity, QCD and W boson samples can be easily discriminated.

2.3 HCAL Performance

TTU group members held several leadership roles during the design, construction, and commissioning of the HCAL in the life of the CMS experiment. Akchurin served as the deputy project manager and technical coordinator of the forward calorimeter (HF) projects. Damgov was the primary data analyzer for the beam test of the HCAL and ECAL production modules in 2002-2006 and a coordinator of the HCAL calibration group until the end of 2014. All members of our group worked on some aspect of

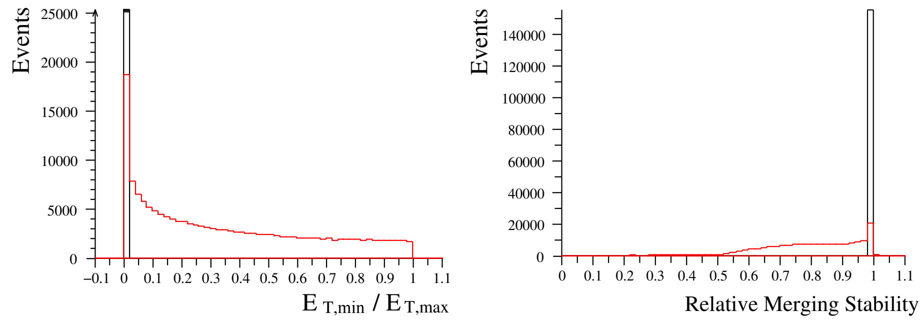


Figure 2.12: Variables that can be used to discriminate boosted W bosons (red) from QCD jets (black) utilizing the scale-invariant jet reconstruction approach. The ratio of the local transverse energies for the two candidate clusters is shown on the left. When a QCD jet is split by the algorithm, the result is very asymmetric: one cluster has much lower energy than the other, and the distribution consists of just the leftmost bin whose height is truncated on this plot. This is not the case for the W decaying into two jets which splits in a much more symmetric manner. The right plot illustrates distributions of a variable which characterizes the stability of the higher-energy cluster with respect to merging as the pattern recognition scale increases. This variable is defined in the infrared-safe manner so that merging of a low energy cluster with a high energy cluster does not significantly affect the stability of the high energy cluster.

HCAL tasks during Run 1.

The TTU group had a strong presence at CERN and made significant contributions to the HCAL DPG and Operation during Run 1. Two postdocs (Damgov and Yazgan) and two graduate students (Libeiro and Kovitanggoon) were at CERN during 2010-2012. Akchurin was also at CERN for a year in 2010-2011 and Lee during the summers of 2010-2012. As the HCAL operation became stable, the TTU presence shifted from CERN to Fermilab in order to have close collaborations with the LPC groups for Run 1 physics analysis but continued to work on the HCAL calibration at the LPC and TTU.

We re-established our continued presence at CERN for Run 2 with Federico De Guio (postdoc) and Kamal Lamichhane (graduate student) starting 2016 and intend to keep for the foreseeable future.

2.3.1 Identification of Electrons in the HF Calorimeter

The HF electron ID efficiency is calibrated using events that contain a precisely measured electron in the central detectors. To reduce background contamination, the invariant mass of the central and HF electron is restricted to the Z boson invariant mass region (80 GeV$< M(e^+e^-) <$ 100 GeV). The same methodology is used for both data and MC events. E_{T} and η-dependent efficiency scale factors are derived from the differences observed between MC and data and applied to MC events. Draiou and Akchurin completed this work and documented it in a detector note in 2015. With the calibration of the HF electromagnetic energy scale, additional opportunities for measuring physical processes at higher rapidities became accessible, *e.g.*, A_{FB} with $Z \to e^+e^-$, as described in Section 2.1.5.3. Figure 2.13 presents the status of this work where a clear Z pole is reconstructed using one electron/positron in the barrel section of the CMS detector and the other in the HF ($\sim$ 19.7 fb^{-1}). We rely on the EM longitudinal shower distribution alone for electron identification, as there is

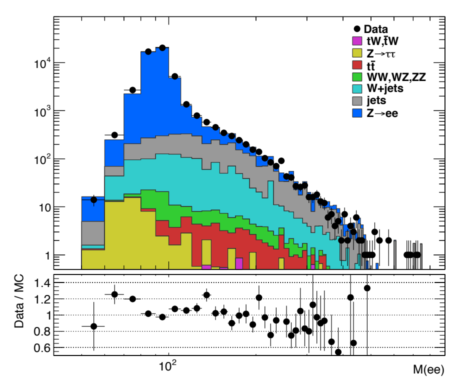
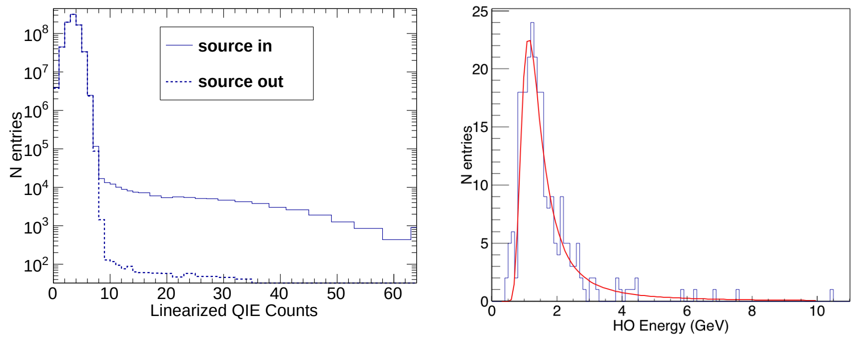


Figure 2.13: Z boson mass is constructed using one electron in the barrel and another in the HF. The Z mass peak is used for absolute energy calibration as well as for other physics studies.



(a) (b)

Figure 2.14: (a) Example of the HF response to the radioactive source (^{60}Co, $\sim$5 mCi) used for relative calibration. The source was mounted on a tip of a wire and pushed through a guide tube in each HF tower. The signal was measured at several depths in HF and set the channel-to-channel relative calibration to better than 5%. (b) The HO signal for prompt muons from early Run 2 data. With the new SiPMs, the HO signal is much larger and cleaner than the one with HPDs in Run 1.

no tracking (or charge ID) in front of the HF.

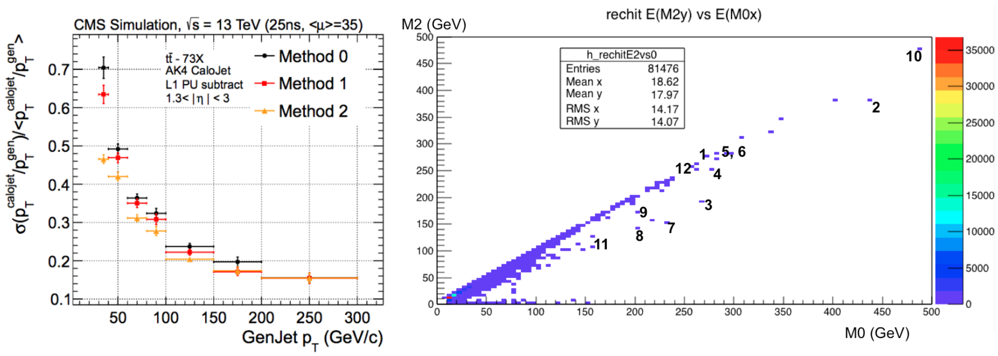
2.3.2 HCAL Calibration

A number of TTU group members made significant contributions to the methodology of HCAL relative and absolute energy calibrations and to detector response stability monitoring. Akchurin, Damgov, and Dragoiu calibrated the endcap and forward calorimeter with physics events ($Z \to e^+e^-$, Z+jet(s) and γ+jets(s)) in Run 1. This period was marked by several new challenges. For the first time, we had to deal with response corrections due to the radiation damage in different parts of the calorimeter. Although calorimeters were equipped with laser/LED/radioactive source systems, it became clear that we had to develop faster and more efficient ways of assessing this damage and recalibrating HCAL. We developed these tools and deployed them in the second half of Run 1. The improvement was manifest in restored jet energy scale stability in the radiation damaged endcap/forward regions. The second important milestone was to provide complete HCAL calibration for the 8 TeV run period. This calibration is used by all published 8 TeV CMS physics results. For Run 2, we reoptimized the calibration of the endcap region with higher level objects: Z+jet(s) and γ+jets(s). HF calibration with the $Z \to ee$ method is described in the previous section.

In 2013-2014, Faulkner participated in the calibration data taking with a radioactive source and derived the first constants for HF with new multi-anode PMTs. He used the calibration method originally developed by Akchurin in 2008 (Figure 2.14(a)). Sonaina Undleeb used the beam splash data to update the relative calibration constants for HB and HE. More recently, Zhixing (Tyler) Wang used prompt muons in the collision data to calibrate the HO response (Figure 2.14(b)).

2.3.3 Pileup Mitigation

Techniques for mitigating the out-of-time pileup are developed by the HCAL Performance Studies Group (PSG). These techniques utilize the time structure of calorimeter signals provided for each HCAL readout channel by a 40 MHz front-end ADC. Nonlinearity of the ADC input amplifier has led to a complex problem without a unique solution. "Method 0" is the CMS code name for the Run 1 reconstruction algorithm, and "Method 1" is the first pileup-aware algorithm developed for Run 2 in 2013-2014. "Method 2," in which a mixture of pulse shapes is fitted to the sequence of ADC counts, is the algorithm in current use.



(a) (b)

Figure 2.15: (a) Energy resolution of calorimeter-based jets for different pileup suppression algorithms in the endcap. (b) Individual channel energies reconstructed by Method 0 and Method 2 for 50 ns data in Run 2. Abnormal hits are most likely due to ion feedback in the HPD. Method 0 picks up the additional signal, while Method 2 successfully trims it off using the pulse shape constraint.

This fit results in better pileup rejection in comparison with the earlier methods, especially in the low p_T region (see Figure 2.15 (a)). As Method 2 is rather expensive computationally, yet another technique, utilizing fast local unfolding, is being developed for use in the CMS high level trigger. Implementation of these algorithms in CMSSW is coordinated by Volobouev.

Kamal Lamichhane studied the effect of pulse shape distortions on the performance of Method 0 and Method 2 using 50 ns beam data at 13 TeV (see Figure 2.15 (b)). We also performed a Monte Carlo study to check the dependence on timing (*i.e.*, fluctuations in the ADC clock phase) and found Method 2 to be sufficiently robust.

2.3.4 Radiation Damage

HF suffered radiation damage. Akchurin and Dudero evaluated all available laser monitoring data from Run 1. Figure 2.16 shows the transmission loss for an HF tower at the largest rapidity ($\eta \sim 5$) and our projection for Run 2. The damage was as expected in Run 1, and the HF will produce enough (Cherenkov) light for adequate energy reconstruction through the end of Run 2.

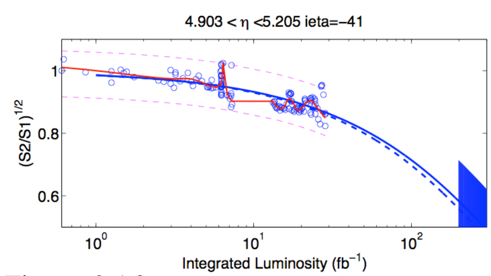


Figure 2.16: At the highest HF rapidity region, the optical transmission of quartz fibers degraded at the end of Run 1 by nearly 15%, as represented by $(S2/S1)^{1/2}$. The projection for Run 2 is shown assuming integrated luminosity up to 300 fb^{-1}. The radiation damage monitoring system, based on OTDR, was first developed at TTU.

2.3.4.1 HCAL Noise Studies

Two types of photodetectors were utilized in HCAL during Run 1: HPDs on HB, HE, and HO; and PMTs on HF. Both types of photodetectors produced occasional multi-TeV-equivalent noise pulses. Although the rates of these pulses are quite low, they create fake $\not{E}_T$ signal and have a strong impact upon physics programs that use large $\not{E}_T$ as a signature. TTU group members Akchurin, Kunori, and Damgov started investigating these types of events in 2006 and pinpointed the cause of "anomalous" signals in HF at beam tests. These signals originate from late developing shower particles impacting the PMT glass window and producing Cherenkov light absorbed by the photosensors. At the ECAL and HCAL combined beam test, we had also identified the "anomalous" signals in ECAL (so-called ECAL spikes) as the avalanche photodiode (APD) nuclear counter effect.

The TTU group exhaustively studied the characteristics of noise signals and established the basis of noise filtering algorithms used at the HLT and in event reconstruction in Run 1. The APD and HF PMT noise signals were clearly created by particles from collisions hitting these photodetectors, while the HPD discharge was spontaneous and random in time. The APD noise filter used timing and energy sharing topology in ECAL. The HPD noise filter used timing and pulse shape, and the PMT noise filter used timing and topology of hits in HF. During Run 1, 24 HF PMTs were replaced with PMTs with thinner glass windows, and the remaining PMTs were replaced during the LS1. We started monitoring the HCAL noise rates (Figure 2.17) and analyzing the HF data to establish a noise filter for the new PMTs.

2.3.5 HCAL DQM Software Development

The entire CMS software framework was ported to a multi-threaded (MT) execution model for all data access. This included extensive changes to the DQM software specific to HCAL. Cowden has taken on this challenge. Migrating the HCAL DQM software modules to comply with the MT framework requires modifications to module's class inheritance hierarchy, which also extends to helper classes and functions. Portions of the HCAL DQM software, in the previous paradigm, made use of a class inheritance for both modules and helper classes in a manner which necessitated non-thread-safe object management. Migrating these portions of the HCAL DQM software demanded expertise in C++, the CMSSW framework, and the new MT specifications. The migration is now complete.

2.3.6 HCAL Monitoring and Prompt Feedback

A TTU team, led by Lee, built a small "Remote Operation Center" (ROC) on campus, and our graduate students took responsibility for the HCAL data certification during Run 1. Kunori, prior to joining TTU, led the HCAL remote monitoring shifts at the Fermilab ROC. Shifters checked daily data using standard monitoring tools and performed prompt offline data analysis. This arrangement proved critical for the HCAL startup in Run 1. Some shifters, generally students and postdocs, were also members of the several analysis groups. They benefited from the ROC activities by effectively incorporating their monitoring knowledge into their analyses of CMS data. As the HCAL and LHC operations became stable,

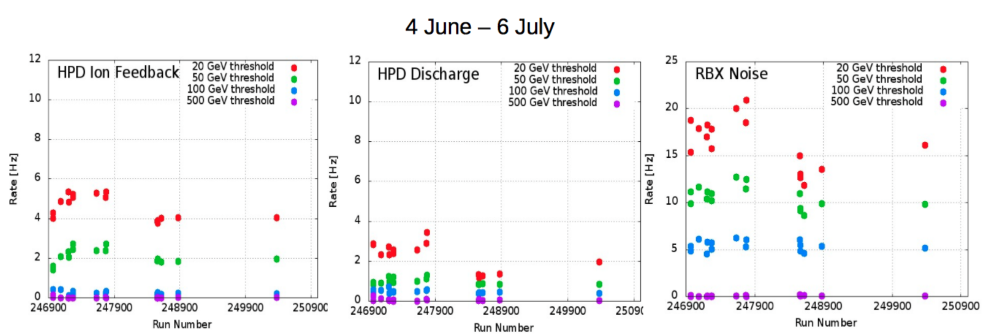


Figure 2.17: Rates of three different types of HCAL noise from the TTU-ROC noise monitoring for June 2015. The HPD Ion Feedback (HPD Discharge) is the low (high) multiplicity noise in the 19 pixel HPD. The RBX noise includes a few types of coherent noises in the readout box on the detector. The noise rates have been monitored since 2010 and are stable. The rates for four different hit energy thresholds are shown with different colors (red 20 GeV, green 50 GeV, blue 100 GeV, and violet 500 GeV).

the monitoring tasks were increasingly more automated, the number of shifts reduced, and the activity eventually stopped altogether.

We revitalized the TTU-ROC for Run 2 startup and established communication protocols with the HCAL operations team at CERN. All of our students have been contributing to the daily monitoring of HCAL and performing offline data analysis for prompt feedback.

2.4 High Granularity Calorimeter (HGC) for the CMS Endcap Region (Phase 2 Upgrade)

Our group had proposed a new type of a combined (EM+HAD), compensating and compact calorimeter (CFC), for the Phase 2 CMS upgrades anticipated for the HL-LHC. Intensive work on the proposal commenced in December 2012, with TTU leading the CFC collaboration (Baylor, CERN, Fermilab, Kansas State, Notre Dame, Rutgers, Saha Institute of Nuclear Physics - Kolkata, Texas A&M, TTU, and Virginia). The CFC development effort continued until April 2014, when the proposal was unfortunately turned down by the CMS management. A summary presentation at CALOR2014 was given by Akchurin and Cowden in April 2014 [58, 59]. We decided to work on the HGC, the winning technology choice for the endcaps in CMS.

HGC technology, based on cooled silicon sensors and dense absorbers (tungsten and copper), was chosen in April 2015 after eliminating the other surviving option, the Shashlik+HE proposal. It is a significant part of the CMS and USCMS Phase 2 upgrade program. In consultation with the CMS Upgrade Management, we identified several areas where we can be effective partners in the R&D, construction, installation, and operation of the HGC. The assembly of silicon sensors into modules is a major undertaking and a critical step in the construction of the HGC. It is anticipated that TTU will be one of two centers in the US producing over six thousand modules (out of $\sim$21.5 thousand total). In addition to the assembly, we will be responsible for initial testing, burn-in, thermal cycling, and shipping the modules to other sites for further assembly into layers (cassettes). We expect to start the prototype production in mid- to late-2017. The final production will take place in 2020 and 2021. In between, we plan to set up the infrastructure and train personnel (1.5 FTE engineers, 7 FTE technicians and students) for this purpose. TTU members have already been participating in beam tests, simulations and the design optimizations.

Chapter 3

Dual-readout Calorimetry - The Detector R&D (Task B)

3.1 Introduction

On August 31, 2011, the CERN Research Board decided to accept the DREAM Collaboration's detector R&D proposal [60] and included it as project RD52 in its official scientific program. As such, Task B in this grant period represents RD52. In this final report, we give a short summary of our work in the study of hadronic shower, some which is unpublished. The talks, as well as all publications in the context of this project, can be found at the RD52 website: *http://highenergy.phys.ttu.edu/dream/results/talks/talks.html*

3.2 The hadronic calorimeter performance

It is quite likely that the discrepancies observed between the experimental data and the Monte Carlo simulations in em showers in dual-readout prototypes are a consequence of the intricacies of the calorimeter structure. Perhaps, specific issues related to the generation of Cherenkov light in the optical fibers play a role as well. The fine details of calorimeter structure should pose less of a problem for hadron showers. Whereas the signal from an em shower depends crucially on the contribution of one single fiber, which may be smaller or larger depending on the precise trajectory of the incoming particle, the signals from hadronic showers are typically composed of the combined contributions of hundreds to thousands of different fibers.

We showed that "standard" hadronic shower simulations gave a reasonable description of the response functions for 100 GeV π^- in the original DREAM copper-fiber calorimeter earlier. Especially the Cherenkov response function was well described by these simulations. On the other hand, the scintillation distribution was more narrow, less asymmetric and peaked at a lower value than for the experimental data. We also found that the hadronic signal non-linearity, which is typical for every non-compensating calorimeter, was much better described for the Cherenkov signals than for the scintillation ones. From additional analyses, we established that the non-relativistic component of the shower development, which is completely dominated by processes at the nuclear level, is rather poorly described by GEANT4, at least by the FTFP_BERT hadronic shower development package, which is the standard used by the ATLAS and CMS collaborations. Both the average size of this component, as well as its event-to-event fluctuations, are at variance with the experimental data. This non-relativistic shower component only plays a role for the scintillation signals, not for the Cherenkov ones.

Yet, some aspects of hadronic shower development that are important for the dual-readout application were found to be in good agreement with the experimental data. As examples, we mention the shape of the Cherenkov response function and the radial shower profiles. Attempts to use the dual-readout technique on simulated shower data reasonably reproduced some of the essential characteristics and advantages of this method: a Gaussian response function, hadronic signal linearity and improved hadronic energy resolution. The fact that the reconstructed beam energy was systematically too low may be ascribed to the problems with the non-relativistic shower component mentioned above.

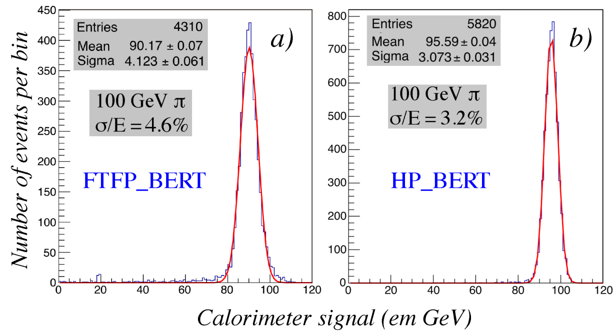


Figure 3.1: The response function for 100 GeV pions in a dual-readout fiber calorimeter based on copper absorber. Results of GEANT4 Monte Carlo simulations, using the FTFP_BERT (*a*) or the HP_BERT (*b*) hadron shower development package.

An important reason for performing these very time consuming simulations was to see if and to what extent the hadronic performance would improve as the detector size is increased. Figure 3.1a shows the signal distribution obtained for 100 GeV π^- in a copper based RD52 calorimeter with a lateral cross section of 65×65 cm^2. The mass of such a ($10\lambda_{\rm int}$ deep) device would be $\sim$ 6 tonnes. According to these simulations, which were carried out with the FTFP_BERT package, the average calorimeter signal, reconstructed with the dual-readout method, would be 90.2 GeV, and the energy resolution would be 4.6%.

In order to see to what extend these simulations depend on the choice of the hadronic shower development package, we repeated these simulations using the high precision version of the hadronic shower simulation package (HP_BERT), which seems to provide a much more elaborate treatment of the numerous neutrons produced in the shower process, but also takes an order of magnitude more CPU time. Figure 3.1b shows the results of this work, which took about 20 minutes of CPU time per event. And indeed, the results show a clear improvement: the average calorimeter signal has increased to 95.6 GeV, and is thus within a few percent equal to that of an em shower developing in the same calorimeter structure (one of the crucial advantages of calorimeters based on the DREAM principle). Also the energy resolution has significantly improved, from 4.6% to 3.2%.

We also generated 4630 events for 200 GeV with the HP_BERT package. This gave an average signal of 191 GeV and an energy resolution of 2.4%. The results of the various simulations are summarized in Figure 3.2.

Figure 3.2 summarizes the situation concerning the hadronic energy resolution, for single pions. It shows experimental data obtained with the RD52 calorimeter, as well as the record setting results published by SPACAL [62]. Also shown are the GEANT4 predictions for a 3×3 and 7×7 module RD52_Cu calorimeter, obtained with the FTFP_BERT package [61], as well as the HP_BERT predictions for 100 and 200 GeV pions. The latter are well described by the dotted line, which corresponds to a resolution of $30\%/\sqrt{E}$.

We believe that the predicted improvement in the performance resulting from an increased detector size is realistic. The resolution of the instruments tested so far in our program was clearly dominated by leakage fluctuations. An increase in the detector volume would reduce the effects of this, in which case resolutions of a few percent seem to be feasible, and would bring the hadronic performance of the RD52 calorimeter at the same level as that of the compensating SPACAL and ZEUS calorimeters, or even better. The potential importance of this is illustrated in Figure 3.3, which shows the results of the simulation of a mixture of hadron showers with energies corresponding to the masses of the W and Z bosons. The two peaks are clearly separated, which is a design requirement for calorimeters at future

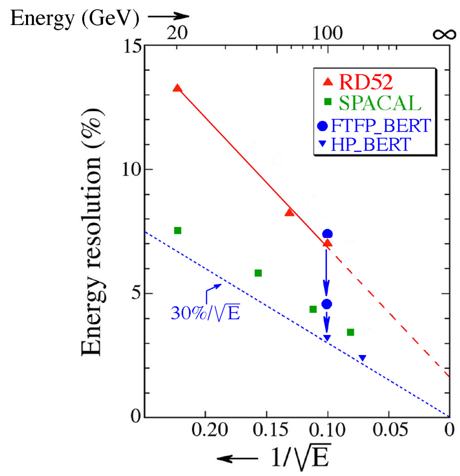


Figure 3.2: The energy resolution for single pions measured with the dual-readout RD52 [63] calorimeter. For comparison, the record resolutions reported for the SPACAL calorimeter are shown as well [62]. Also shown are the results of GEANT4 simulations for the current and full-size RD52 copper-fiber calorimeter, using the FTFP_BERT hadronic shower package [61], as well as the results obtained with the HP_BERT package for the full-size copper-fiber calorimeter [64].

e^+e^- colliders. Of course, just like with all other hadron calorimeter results, these simulations need to be verified experimentally in order to establish how realistic they really are.

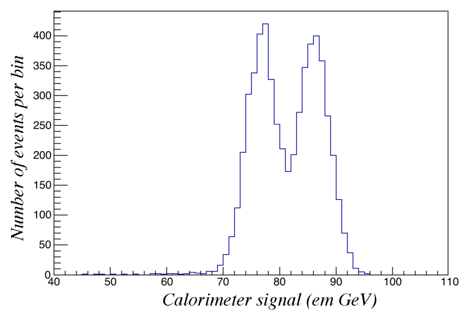


Figure 3.3: The response curve for a mixture of hadrons with energies corresponding to the W and Z masses. Results of simulations with the high precision GEANT4 package.

It should be emphasized that the results shown in Figures 3.1 - 3.3 are for single hadrons. There is an important reason why the jet energy resolution of copper based dual-readout fiber calorimeters may also be expected to be much better than that of the high-Z compensating calorimeters [65]. A sizable component of the jet consists of soft hadrons, which range out rather than developing showers. The response of calorimeters such as ZEUS to these particles is considerably larger than the response to the showering γs and high-energy hadrons. The scale for the difference between these responses is set by the e/mip value, which was measured to be 0.62 in ZEUS and 0.72 in SPACAL. The advantage of an absorber material with much lower Z is an e/mip value that is much closer to 1 (the value at which point this effect ceases to play a role). For our copper based dual-readout fiber calorimeter, an e/mip value of 0.84 was found. The possibility to measure jets with superior resolution compared to previously built high-Z compensating calorimeters was one of the main reasons why we had embarked on the dual-readout project.

Bibliography

[1] XVth International Conference on Calorimetry in High Energy Physics (CALOR2012), Santa Fe, N.M., June 2012 (calor2012.ttu.edu), Proceedings of the XVth International Conference on Calorimetry in High Energy Physics, J. Phys. Conf. Ser. Vol. **404** (2013)

[2] CMS Collaboration, "Search for Dijet Resonances in 7 TeV *pp* Collisions at CMS", Phys. Rev. Lett. **105**, 211801 (2010)

[3] CMS Collaboration, "Search for Resonances in the Dijet Mass Spectrum from 7 TeV *pp* Collisions at CMS", Phys. Lett. B **704**, 123 (2011)

[4] CMS Collaboration, "Search for narrow resonances and quantum black holes in inclusive and b-tagged dijet mass spectra from *pp* collisions at $\sqrt{s}$ = 7 TeV", J. High Energy Phys. **01**, 013 (2013)

[5] CMS Collaboration, "Search for narrow resonances using the dijet mass spectrum in *pp* collisions at $\sqrt{s}$ = 8 TeV", Phys. Rev. D **87**, 114015 (2013)

[6] CMS Collaboration, "Search for resonances and quantum black holes using dijet mass spectra in proton-proton collisions at $\sqrt{s}$ = 8 TeV", Phys. Rev. D **91**, 052009 (2015)

[7] CMS Collaboration, "Search for Quark Compositeness with the Dijet Centrality Ratio in *pp* Collisions at $\sqrt{s}$= 7 TeV", Phys. Rev. Lett. **105**, 262001 (2010)

[8] CMS HCAL/ECAL Collaborations, "The CMS Barrel Calorimeter Response to Particle Beams from 2 to 350 GeV/*c*", Eur. Phys. J. **C 60**, 359 (2009)

[9] Kazim Gümüş, TTU Ph.D. Thesis, "Search for New Physics in the Compact Muon Solenoid (CMS) Experiment and the Response of the CMS Calorimeters to Particles and Jets", FERMILAB-THESIS-2008-39 & CERN-THESIS-2008-066 (2008)

[10] Chiyoung Jeong, TTU Ph.D. Thesis, "New Physics Search in Dijet Mass Spectrum with Compact Muon Solenoid", FERMILAB-THESIS-2011-40 & CERN-THESIS-2011-267 (2011)

[11] N. Arkani-Hamed, S. Dimopoulous, and G. Dvali, "The Hierarchy Problem and New Dimensions at Millimeter", Phys. Letts. B **492**, 263 (1998)

N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, "Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity", Phys. Rev. D 59 (1999) 086004

I. Antoniadis, K. Benakli, and M. Quiros, “Direct collider signatures of large extra dimensions”, Phys. Lett. B 460 (1999) 176

G. Giudice, R. Rattazzi, and J. Wells, “Quantum gravity and extra dimensions at high-energy colliders”, Nucl. Phys. B 544 (1999) 3

E. Mirabelli, M. Perelstein, and M. Peskin, “Collider signatures of new large space dimensions”, Phys. Rev. Lett. 82 (1999) 2236

[12] CMS Collaboration, “Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy”, Phys. Rev. Lett. **108**, 261803 (2012)

[13] CMS Collaboration, “Search for New Physics with a Monojet and Missing Transverse Energy in pp Collisions at $\sqrt{s}$ = 7 TeV”, Phys. Rev. Lett. **107**, 201804 (2011)

[14] CMS Collaboration, “Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV”, J. High Energy Phys. **09**, 094 (2012)

[15] CMS Collaboration, “Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8$ TeV”, Eur. Phys. J. **C 75**, 235 (2015)

[16] H. Georgi, “Unparticle Physics”, Phys. Rev. Lett. **98**, 221601 (2007)

[17] CMS Collaboration, “Search for direct production of stops decaying to a charm and LSP using the monojet + MET final state”, CMS PAS SUS-13-009 (2013)

[18] CMS Collaboration, “Projections at 14 TeV for Dark Matter Searches in the Monojet Final State Using the Upgraded CMS Detector”, CMS PAS FTR-13-011 (2013)

[19] B. Dutta, Y. Gao, and T. Kamon, “Probing Light Nonthermal Dark Matter at the LHC”, Phys. Rev. D **89**, 096009 (2014)

[20] Y. Bai and J. Berger, “Fermion Portal Dark Matter”, J. High Energy Phys. **11**, 171 (2013)

[21] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. **B 716**, 30 (2012)

[22] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. **B 716**, 1 (2012)

[23] CMS Collaboration, “Search for a standard-model-like Higgs boson with a mass in the range 145 to 1000 GeV at the LHC”, Eur. Phys. J. **C 73**, 2469 (2013)

[24] CMS Collaboration, “Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons”, J. High Energy Phys. **10** 144 (2015)

[25] K. Hagiwara, S. Ishihara, R. Szalapski and D. Zeppenfeld, “Low energy effects of new interactions in the electroweak boson sector”, Phys. Rev. D **48**, 2182 (1993)

[26] CMS Collaboration, “Measurement of the sum of WW and WZ production with W+dijet events in pp collisions at $\sqrt{s} = 7$ TeV”, Eur. Phys. J. **C 73**, 2283 (2013)

[27] CMS Collaboration, “Measurement of WW+WZ production in semi-leptonic decays in pp collisions at $\sqrt{s} = 8$ TeV” CMS PAS SMP-13-008 (2013)

[28] CMS Collaboration, "Measurement of WW+WZ cross section and investigation of anomalous gauge boson couplings in semi-leptonic decays in pp collisions at $\sqrt{\text{s}}$ = 8 TeV", CMS Analysis Note, AN-2012-464 (2012)

[29] The CMS Collaboration, "A Search for $WW\gamma$ and $WZ\gamma$ and Constraints on Anomalous Quartic Gauge Couplings in pp Collisions at $\sqrt{s} = 8$ TeV", Phys. Rev. D **90**, 032008 (2014)

[30] K.A. Olive *et al.,* (Particle Data Group), "The Review of Particle Physics", Chin. Phys. C, **38**, 090001 (2014)

[31] CMS Collaboration, "Rapidity distributions in exclusive $Z+$ jet and $\gamma+$ jet events in pp collisions at $\sqrt{s}$= 7 TeV", Phys. Rev. D **88**, 112009 (2013)

[32] T. Gleisberg *et al.,* "Event generation with Sherpa 1.1", J. High Energy Phys. **0902**, 007 (2009)

[33] J. Alwall *et al.,* "MadGraph 5: Going Beyond", J. High Energy Phys. **06**, 128 (2011)

[34] J. Campbell, K. Ellis, and C. Williams, "MCFM - Monte Carlo for FeMtobarn processes" (mcfm.fnal.gov)

[35] Kittikul Kovitanggoon, TTU Ph.D. Thesis, "Study of Jets Production in Association with a Z Boson in pp Collisions at 7 and 8 TeV with the CMS Detector", FERMILAB-THESIS-2014-16 & CERN-THESIS-2014-088 (2014)

[36] CMS Collaboration, "Measurement of the differential production cross section of Z bosons in association with jets in pp collisions at t $\sqrt{s}$ = 7 TeV", CMS PAS SMP-13-007 (2013)

[37] CMS Collaboration, "Measurement of the double differential cross section of Z bosons produced in association with jets in pp collisions at $\sqrt{s}$ = 8 TeV", CMS PAS SMP-14-009 (2014)

[38] CMS Collaboration, "Forward-backward asymmetry of Drell-Yan lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV", Phys. Lett. B **718**, 752 (2013)

[39] Youn Jung Roh, TTU Ph.D. Thesis, "Measurement of the Forward-backward Asymmetry in γ/Z Boson to Dileptons in Compact Muon Solenoid at a Center-of-Mass Energy of 7 TeV", FERMILAB-THESIS-2011-47 & CERN-THESIS-2011-266 (2011)

[40] CMS Collaboration, "Forward-backward asymmetry of Drell-Yan lepton pairs in pp collisions at $\sqrt{s}$ = 8 TeV", Eur. Phys. J. C **76** 25 (2016)

[41] CMS Collaboration, "Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s}$ = 2.76 TeV", Eur. Phys. J. C **76** 265 (2016)

[42] Z. Nagy, "Next-to-leading order calculation of three-jet observables in hadron-hadron collisions" Phys. Rev. D **68**, 094002 (2013)

[43] H.L. Lai *et al.*, "New parton distributions for collider physics", Phys. Rev. D **82**, 074024 (2010)

[44] CMS Collaboration, "Measurement of the double-differential inclusive jet cross section at $\sqrt{s} =$ 8 TeV with the CMS detector", CMS PAS SMP-12-012 (2012)

[45] CMS Collaboration, "Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s}$ = 13 TeV", Phys. Rev. Lett. **116**, 071801 (2016)",

[46] CMS Collaboration, “Search for dark matter with jets and missing transverse energy at 13 TeV”, CMS PAS EXO-15-003 (2016)

[47] CMS Collaboration, “Search for dark matter production in association with jets, or hadronically decaying W or Z boson at $\sqrt{s}$ = 13 TeV”, CMS PAS EXO-16-013 (2015)

[48] CMS Collaboration, “Search for massive resonances decaying into pairs of boosted W and Z bosons at $\sqrt{s}$ = 13 TeV”, CMS PAS EXO-15-002 (2015)

[49] CMS Collaboration, “Search for a narrow resonance decaying to WW $\rightarrow l\nu qq$ in the mass range from 600-1000 GeV”, CMS PAS B2G-16-004 (2016)

[50] CMS Collaboration, “Combination of searches for WW, WZ, ZZ, WH, and ZH resonances at $\sqrt{s}$ = 8 and 13 TeV”, CMS PAS B2G-16-007 (2015)

[51] CMS Collaboration, “Missing transverse energy performance of the CMS detector”, JINST **6** P09001 (2011)

[52] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s}$ = 8 TeV”, JINST **10** P02006 (2015)

[53] I. Volobouev, “FFTJet: The User Manual”, http://fftjet.hepforge.org (2014)

[54] I. Volobouev, “FFTJet: A Package for Multiresolution Particle Jet Reconstruction in the Fourier Domain”, arXiv:0907.0270 [hep-ex] (2009)

[55] I. Volobouev, “Multiresolution Jet Reconstruction with FFTJet”, J. Phys. Conf. Ser. **293**, 012028 (2011)

[56] T. Lindeberg, “Scale-Space Theory in Computer Vision”, Kluwer Academic Publishers (1994)

[57] M.C. Minnotte and D.W. Scott, “The Mode Tree: a Tool for Visualization of Nonparametric Density Features”, Journal of Computational and Graphical Statistics **2**, 51 (1993)

[58] N. Akchurin, “Combined Forward Calorimetry Option for Phase II CMS Endcap Upgrade”, J. Phys. Conf. Ser. **587**, 012015 (2015)

[59] C. S. Cowden, “Object Reconstruction in Non-Pointing Geometry”, J. Phys. Conf. Ser. **587** 012017 (2015)

[60] DREAM Collaboration (Wigmans R) 2010, CERN-SPSC-2010-012/SPSC-M-771.

[61] Akchurin N *et al.* 2014, “Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter”, Nucl. Instr. and Meth. in Phys. Res. **A762** (2014) 100 - 118.

[62] Acosta D *et al.*, Nucl. Instr. and Meth. in Phys. Res. **A308** (1991) 481.

[63] Wigmans R 2013, Nucl. Instr. and Meth. in Phys. Res. **A732** (2013) 475.

[64] Wigmans R *et al.*, *New results from the RD52 project*, Proc. of the 13th Int. Conf. “Frontier Detectors for Frontier Physics”, Elba, 2015, to be published in Nucl. Instr. and Meth. in Phys. Res. .

[65] DREAM Collaboration (Wigmans R) 2012, CERN-SPSC-2012-014; SPSC-SR-100.

Appendix A

Publications by Members of the TTU group
May 2012 - March 2016

- CMS Collaboration (N. Akchurin, J. Damgov, S.W. Lee)
  Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy
  Phys. Rev. Lett. **108**, 261803 (2012)

- CMS Collaboration (N. Akchurin, P. Dudero, S.W. Lee)
  Study of the dijet mass spectrum in pp $\rightarrow$ W + jets events at $\sqrt{s}$ = 7 TeV,
  Phys. Rev. Lett. **109** 251801 (2012)

- N. Akchurin, et al.,
  Detection of electron showers in Dual-Readout crystal calorimeters,
  Nucl. Instr. and Meth. in Phys. Res. A 686 (2012) 125.

- CMS Collaboration (C. Jeong, S.W. Lee)
  Search for narrow resonances and quantum black holes in inclusive and b-tagged dijet mass spectra from pp collisions at $\sqrt{s}$ = 7 TeV,
  J. High Energy Phys. **01** 013 (2013)

- CMS Collaboration (N. Akchurin, K. Kovitanggoon, S.W. Lee, Y. Roh, E. Yazgan)
  Forward-backward asymmetry of Drell-Yan lepton pairs in pp collisions at $\sqrt{s}$ = 7 TeV,
  Phys. Lett. B **718** 752 (2013)

- CMS Collaboration (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of the sum of WW and WZ production with W+dijet events in pp collisions at $\sqrt{s}$ = 7 TeV,
  Eur. Phys. J. C **73** 2283 (2013)

- CMS Collaboration (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for a standard-model-like Higgs boson with a mass in the range 145 to 1000 GeV at the LHC,
  Eur. Phys. J. C **73** 2469 (2013)

- CMS Collaboration (S.W. Lee)
  Search for narrow resonances using the dijet mass spectrum in pp collisions at $\sqrt{s}$ = 8 TeV,
  Phys. Rev. D **87** 114015 (2013)

- CMS Collaboration (N. Akchurin, J. Damgov, S.W. Lee)
  Measurement of the production cross section for $Z\gamma \rightarrow \nu\nu\gamma$ in pp collisions at $\sqrt{s}$ = 7 TeV and limits on $ZZ\gamma$ and $Z\gamma\gamma$ triple gauge boson couplings,
  J. High Energy Phys. **10** 64 (2013)

- CMS Collaboration (N. Akchurin, K. Kovitanggoon, S.W. Lee)
  Rapidity distributions in exclusive Z + jet and photon + jet events in pp collisions at $\sqrt{s} = 7$ *TeV,*
  Phys. Rev. D **88** 112009 (2013)

- CMS Collaboration (N. Akchurin, J. Damgov, P. Dudero, J. Faulkner, S.W. Lee)
  A search for $WW\gamma$ *and* $WZ\gamma$ *production and constraints on anomalous quartic gauge couplings in pp collisions at* $\sqrt{s} = 8$ *TeV,*
  Phys. Rev. D **90**, 032008 (2014)

- N. Akchurin, et al.,
  The electromagnetic performance of the RD52 fiber calorimeter,
  Nucl. Instr. and Meth. in Phys. Res. A 735 (2014) 130.

- N. Akchurin, et al.,
  Particle identification in the longitudinally unsegmented RD52 calorimeter,
  Nucl. Instr. and Meth. in Phys. Res. A 735 (2014) 120.

- N. Akchurin, et al.,
  Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter,
  Nucl. Instr. and Meth. in Phys. Res. A 762 (2014) 100.

- CMS Collaboration (S. Kunori, S.W. Lee)
  Search for resonances and quantum black holes using dijet mass spectra in proton-proton collisions at $\sqrt{s} = 8$ *TeV,*
  Phys. Rev. D **91**, 052009 (2015)

- CMS Collaboration (S. Kunori)
  Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8$ *TeV,*
  Eur. Phys. J. C **75** 235 (2015)

- CMS Collaboration (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for a Higgs boson in the mass range from 145 to 1000 GeV decaying to a pair of W or Z bosons,
  J. High Energy Phys. **10** 144 (2015)

- CMS Collaboration (N. Akchurin, C. Dragoiu, S. Kunori, S.W. Lee, Z. Wang)
  Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13$ *TeV,*
  Phys. Rev. Lett. **116**, 071801 (2016)

- CMS Collaboration (S.W. Lee, T. Libeiro. Volobouev)
  Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ *TeV,*
  Eur. Phys. J. C **76** 265 (2016)

- CMS Collaboration (N. Akchurin, C. Dragoiu, S.W. Lee)
  Forward-backward asymmetry of Drell-Yan lepton pairs in pp collisions at $\sqrt{s} = 8$ *TeV,*
  Eur. Phys. J. C **76** 25 (2016)

Technical Reports by Members of the TTU group

May 2012 - March 2016

- J.P. Chou *et al*., (C. Jeong, S.W. Lee)
  Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at $\sqrt{s}$ *= 7 TeV*
  CMS Analysis Note, AN-2012-012, 2012
- L. Lebolo *et al*., (N. Akchurin, K. Kovitanggoon, S.W. Lee)
  Angular Distribution of Z Bosons in Z+Jet Events Using 2011 Data
  CMS Analysis Note, AN-2012-037, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, S.W. Lee)
  Limits on the Anomalous $ZZ\gamma$ *and* $Z\gamma\gamma$ *couplings at* $\sqrt{s}$ *= 7 TeV where Z decays invisibly*
  CMS Analysis Note, AN-2012-093, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for a Higgs Boson in $qqH \to W(l\nu)\ W(jj)$ *+ 2 Tag Jets*
  CMS Analysis Note, AN-2012-139, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for the Standard Model Higgs boson in the $H \to WW \to l\nu jj$ *decay with 2012 data*
  CMS Analysis Note, AN-2012-193, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of WW+WZ cross section in semi-leptonic decays in pp collisions at $\sqrt{s}$ *= 7 TeV*
  CMS Analysis Note, AN-2012-224, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Searches for new physics in the $WW \to l\nu j$ *final state with hadronic W bosons merged into a single jet*
  CMS Analysis Note, AN-2012-381, 2012
- J.P. Chou *et al*., (S.W. Lee)
  Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2012-463, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for the Standard Model Higgs boson in the $H \to WW \to l\nu jj$ *decay with 2012 HCP data*
  CMS Analysis Note, AN-2012-463, 2012
- B. Bilin *et al*., (S.W. Lee)
  Search for Narrow Resonances using the Dijet Mass Spectrum in pp Collisions at $\sqrt{s}$ *= 8 TeV with full 2012 dataset*
  CMS Analysis Note, AN-2012-455, 2012
- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for an SM-like Higgs boson in the $H \to WW \to l\nu jj$ *decay with the full 2012 data*
  CMS Analysis Note, AN-2012-463, 2012

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of WW+WZ cross section and investigation of anomalous gauge boson couplings in semi-leptonic decays in pp collisions at $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2012-464, 2012

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for a Higgs Boson in qqH $\rightarrow$ *W(l*ν*) W(jj) + 2 Tag Jets at* $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2012-465, 2012

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of WW+ 2-jet production at $\sqrt{s}$ *= 8 TeV and investigation of events with vector boson fusion topology*
  CMS Analysis Note, AN-2012-466, 2012

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of WW+ 2-jet production at $\sqrt{s}$ *= 8 TeV and investigation of events with vector boson fusion topology*
  CMS Analysis Note, AN-2012-466, 2012

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, J. Faulkner, S.W. Lee)
  Measurement of WWγ *+ WZ*γ *cross section and investigation of anomalous gauge boson couplings in semi-leptonic decays in pp collisions at* $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2012-479, 2012

- N. Akchurin, C. Cowden, and P. Dudero,
  HF Fiber Radiation Damage
  CMS Analysis Note, DN-2013-018, 2013

- B. Asavapibhop *et al*., (K. Kunori)
  Search for stop production using monojet events at 8 TeV
  CMS Analysis Note, AN-2013-118, 2013

- N. Akchurin *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Measurement of the electroweak production cross section of a W boson with two jets in pp collisions at $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2013-123, 2013

- B. Bilin *et al*., (K. Kovitanggoon, S.W. Lee)
  Study of differential cross section of jets associated to Z boson in pp collisions at $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2013-224, 2013

- A. Bhatti *et al*., (K. Kunori)
  Projections at 14 TeV for Dark Matter Searches in the Monojet Final State Using the Upgraded CMS Detector
  CMS Analysis Note, AN-2013-294, 2013

- C. Cowden *et al*., (N. Akchurin, C. Cowden, S.W. Lee)
  Search for Dirac Magnetic Monopoles in pp Collisions at $\sqrt{s}$ *= 8 TeV*
  CMS Analysis Note, AN-2013-402, 2013

- G. Alves *et al*., (J. Damgov, P. Dudero, S.W. Lee),
  Semi-leptonic decay of HWW at high mass in exclusive jet bins
  CMS Analysis Note, AN-2013-414, 2013

- T. Libeiro and I. Volobouev,
  Calibration of FFTJet Algorithm for the CMS Experiment
  CMS Analysis Note, AN-2014-034, 2014

- C. Dragoiu, N. Akchurin, and S.W. Lee
  Measurement of the Forward-Backward Asymmetry of Electron Pairs in itpp Collisions at $\sqrt{s} = 8$ *TeV*
  CMS Analysis Note, AN-2014-050, 2014

- J.P. Chou *et al*., (K. Kunori, S.W. Lee)
  Search for dijet resonances at $\sqrt{s} = 8$ *TeV with data scouting*
  CMS Analysis Note, AN-2014-104, 2014

- B. Bilin *et al*., (K. Kovitanggoon, S.W. Lee)
  Study of double ($d^2\sigma/dp_T dy^j$) *and triple* ($d^3\sigma/dp_T dy^j dy^Z$) *differential cross sections of Z + jets in pp collisions at* $\sqrt{s} = 8$ *TeV*
  CMS Analysis Note, AN-2014-115, 2014

- T. Libeiro *et al*., (S.W. Lee, T. Libeiro, I. Volobouev)
  Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 2.76$ *TeV and ratio to the inclusive jet cross section at* $\sqrt{s} = 8$ *TeV with the CMS detector*
  CMS Analysis Note, AN-2014-160, 2014

- S. Ahuja *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for new diboson resonances in semileptonic and hadronic final states at $\sqrt{s} = 13$ *TeV*
  CMS Analysis Note, AN-2015-037, 2015

- N. Saoulidou *et al*., (N. Akchurin, C. Cowden, C. Dragoiu, S. Kunori, S.W. Lee)
  Search for narrow resonances using the dijet mass spectrum in proton-proton collisions at $\sqrt{s} = 13$ *TeV (Phys14 MC analysis)*
  CMS Analysis Note, AN-2015-063, 2015

- M. Baber *et al*., (N. Akchurin, C. Cowden, S. Kunori, S.W. Lee, S. Undleeb)
  Search for New Physics in the Monojet Final State
  CMS Analysis Note, AN-2015-072, 2015

- N. Saoulidou *et al*., (N. Akchurin, C. Cowden, C. Dragoiu, S. Kunori, S.W. Lee)
  Search for narrow resonances using the dijet mass spectrum with 42 pb^{-1} *of proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
  CMS Analysis Note, AN-2015-175, 2015

- I. Dumanoglu *et al*., (S. Kunori)
  Noise Filter Performance studies for CMS HF by comparing new and old PMTs using Collection of data taken in 2012
  CMS Detector Note, DN-2015-024, 2015

- S. Ahuja *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Common note on searches for new diboson resonances in semileptonic and hadronic final states at $\sqrt{s} = 13$ TeV
  CMS Analysis Note, AN-2015-196, 2015

- S. Ahuja *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for new WV diboson resonances in semileptonic final states at $\sqrt{s} = 13$ TeV
  CMS Analysis Note, AN-2015-197, 2015

- S. Ahuja *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Search for new VZ resonpances in semileptonic final states at $\sqrt{s} = 13$ TeV
  CMS Analysis Note, AN-2015-200, 2015

- J. Faulkner *et al*., (J. Damgov, P. Dudero, J. Faulkner, S.W. Lee)
  A Search for $WW\gamma$ and $WZ\gamma$ Production and Anomalous Quartic Gauge Couplings in pp Collisions at $\sqrt{s} = 13$ TeV
  CMS Analysis Note, AN-2015-276, 2015

- S. Ahuja *et al*., (N. Akchurin, J. Damgov, P. Dudero, S.W. Lee)
  Combination of di-boson resonance searches at 8 and 13 TeV
  CMS Analysis Note, AN-2016-042, 2016

- N. Akchurin *et al*., (N. Akchurin, C. Cowden, S. Kunori, S.W. Lee, S. Undleeb)
  Search for New Physics With Jets and Missing Transverse Energy
  CMS Analysis Note, AN-2016-062, 2016

- T. Arnoldus Du Pree *et al*., (S.W. Lee)
  Combined Dark Matter interpretation of Exotica MET+X searches
  CMS Analysis Note, AN-2016-144, 2016

- N. Akchurin *et al*., (N. Akchurin, S. Kunori, S.W. Lee)
  Search for dijet resonances from data scouting at $\sqrt{s} = 13$ TeV using 1.9 fb^{-1} collected in 2015
  CMS Analysis Note, AN-2016-145, 2016

- N. Akchurin *et al*., (N. Akchurin, S. Kunori, S.W. Lee)
  Search for dijet resonances using Calo scouting at $\sqrt{s} = 13$ TeV using data collected in 2015
  CMS Analysis Note, AN-2016-156, 2016

- N. Saoulidou *et al*., (F. De Guio, Z. Wang, S.W. Lee)
  Search for dijet resonances using Calo scouting at 13 TeV using data collected in 2016
  CMS Analysis Note, AN-2016-202, 2016

Talks by Members of the TTU group
May 2012 - March 2016

- R. Wigmans,
New Results from the RD52 (DREAM) Project,
Plenary talk given at the Conference on Frontier Detectors for Frontier Physics, Elba, Italy, May 2012

- R. Wigmans,
The New RD52 (DREAM) Fiber Calorimeter,
Plenary talk given at the XVth International Conference on Calorimetry in High Energy Physics, Sante Fe, NM, Jun. 2012

- C. Cowden,
Detection of Clustering Instabilities for Sequential Recombination Algorithms,
Plenary talk given at the XVth International Conference on Calorimetry in High Energy Physics, Sante Fe, NM, Jun. 2012

- N. Akchurin,
Closing Remarks,
Plenary summary talk of the XVth International Conference on Calorimetry in High Energy Physics, Sante Fe, NM, Jun. 2012

- J. Damgov,
Recent Results from a Search for Dark Matter Production in the CMS Experiment,
IDM 2012: Identification of Dark Matter, 2012, Chicago, IL, Jul. 2012

- N. Akchurin,
Higgs Searches at the CMS Experiment at the LHC,
Invited plenary talk given at Joint Fall 2012 Meeting of the Texas Sections of the APS, Nov 2012, Lubbock, TX, Nov. 2012

- P. Dudero,
Search for Higgs Decaying to WW at CMS,
Parallel talk given at Hadron Collider Physics Symposium 2012, Kyoto, Japan, Nov. 2012

- J. Damgov,
Using Di-boson Events in Searches for New Physics with CMS Detector,
Invited colloquium given at Texas Tech University, Lubbock, TX, Nov. 2012

- R. Wigmans,
The Dual-Readout Approach to Calorimetry,
Plenary talk given at the 13th Vienna Conference on Instrumentation, Vienna, Austria, Feb. 2013

- S.W. Lee,
Review of CMS Exotic Results,
Plenary talk given at Aspen Winter Conference: Higgs Quo Vadis, Aspen, CO, Mar. 2013

- N. Akchurin & S.W. Lee,
The God Particle-A New Frontier in Physics,
Invited public lectures, OLLI, Lubbock, TX, Apr. 2013

- S.W. Lee,
Review of New Particle Searches from ATLAS and CMS,
Invited plenary talk given at APS April Meeting 2013, Denver, CO, Apr. 2013

- R. Wigmans,
Dual-Readout Calorimetry - Excellent Measurement Pecision for ALL Particles and NO Calibration Issues,
Invited talk given at the INFN workshop on the International Linear Collider, Como, Italy, May 2013

- R. Wigmans,
Dual-Readout Calorimetry - Excellent Measurement Precision for ALL Particles and NO Calibration issues,
Invited talk given at the High Energy Physics Conference of the European Physical Society, Stockholm, Sweden, July 2013

- S. Kunori,
Dark Matter Searches at CMS,
Plenary talk given at the International Workshop on the Interconnection between Particle Physics and Cosmology, Deadwood, SD, July 2013

- S.W. Lee,
Review of New Particle Searches at Large Hadron Collider,
Invited talk given at US-Korea Conference on Science, Technology and Entrepreneurship 2013, Newark, NJ, Aug. 2013

- J. Damgov,
Search for Dark Matter using Monophoton Events at 7 TeV,
Plenary talk given at Dark Matter at the LHC, Chicago, IL, Sep. 2013

- J. Faulkner,
aQGC from VWγ at CMS,
Plenary talk given at Anomalous Quartic Gauge Couplings Helmholtz Alliance Workshop, Dresden, Germany, Oct. 2013

- S.W. Lee,
Recent Results from the CMS Experiment at LHC,
Invited Seminar at Korea Advanced Institute of Science and Technology, Daejeon, Korea, Nov. 2013

- N. Akchurin,
Polarization as a Tool in High Energy Calorimetry,
Plenary talk given at 13^{th} Vienna Conference on Instrumentation, Vienna, Austria, Feb. 2014

- R. Wigmans,
  Hadron Calorimetry Options for Future Experiments in Particle Physics,
  Invited talk given at the Bethe Forum on Particle Detectors - Trends and Challenges, Bonn, Germany, Apr. 2014

- R. Wigmans,
  On Wrong and Correct Methods to Analyze and Interpret Calorimeter Test Beam Data,
  Invited talk given at the Bethe Forum on Particle Detectors - Trends and Challenges, Bonn, Germany, Apr. 2014

- R. Wigmans,
  Calorimetry - A tutorial about the most important instruments in modern particle physics experiments,
  Invited Tutorial given at the 16th International Conference on Calorimetry in High Energy Physics, Giessen, Germany, Apr. 2014

- C. Cowden,
  Object Reconstruction with Non-pointing Combined Forward Calorimeter,
  Plenary talk given at 16th International Conference on Calorimetry for High-Energy Physics, Giessen. Germany, Apr. 2014

- N. Akchurin,
  Combined Forward Calorimetry (CFC) for Phase II CMS Upgrade,
  Plenary talk given at 16th International Conference on Calorimetry for High-Energy Physics, Giessen. Germany, Apr. 2014

- J. Damgov,
  Multiboson Measurements, and Triple, and Quartic Gauge Couplings with the CMS,
  Parallel talk given at the Second Annual Conference on Large Hadron Collider Physics, New York, NY, June 2014

- S.W. Lee,
  Summary of QCD/HF sessions
  Parallel talk given at the Second Annual Conference on Large Hadron Collider Physics, New York, NY, June 2014

- J. Damgov,
  Dark Matter Searches at CMS,
  Plenary talk given at Dark Interactions: Perspectives from Theory and Experiment, BNL, Upton, NY, June 2014

- P. Dudero,
  Double-boson and Triple-boson Production from CMS and Limits on aTGC and QGC,
  Parallel talk given at 37th International Conference on High Energy Physics, Valencia, Spain, July 2014

- S.W. Lee,
  What's Next for the Large Hardon Collider?,

Invited talk given at US-Korea Conference on Science, Technology and Entrepreneurship 2014, San Francisco, CA, Aug. 2014

- S.W. Lee,
  High p_T Jet Spectra and α_s Measurements up to the Scale of the Top,
  Plenary talk given at XXXIV Physics in Collisions, Bloomington, IN, Sep. 2014

- J. Faulkner,
  Triboson Results at CMS,
  Plenary talk given at Multi-Boson Interactions Workshop, BNL, Upton, NY, Oct. 2014

- S.W. Lee,
  Recent Results on Jet Physics from CMS Experiment at LHC,
  Invited Seminar at Lawrence Berkeley National Laboratory, Berkeley, CA, Feb. 2015

- C. Dragoiu,
  W/Z Results from CMS,
  Parallel talk given at the XXIII International Workshop on Deep-inelastic scattering and related subjects, Dallas, TX, Apr. 2015

- J. Damgov,
  Multiboson Measurements and Exclusive W^+W^- Production and Constraints on Anomalous Quartic Gauge Couplings Measured with the CMS Experiment,
  Parallel talk given at the XXIII International Workshop on Deep-inelastic scattering and related subjects, Dallas, TX, Apr. 2015

- S.W. Lee,
  Summary of WG4 QCD and Hadronic Final States,
  Plenary talk given at the XXIII International Workshop on Deep-inelastic scattering and related subjects, Dallas, TX, Apr. 2015

- R. Wigmans,
  New Results on the RD52 Project,
  Invited talk given at the 13th Pisa Meeting on Frontier Detectors for Frontier Physics, Elba, Italy, May 2015

- J. Damgov,
  Cerium-doped Scintillating Fused-silica Fibers,
  Parallel talk given at the 13th International Conference on Inorganic Scintillators and Their Applications, Berkeley, CA, June 2015

- P. Dudero,
  Multiboson Production at CMS,
  Parallel talk given at the European Physical Society Conference on High Energy Physics 2015, Vienna, Austria, July 2015

- J. Damgov,
  Searches for Boosted Dibosons in CMS,

Parallel talk given at the 23rd International Conference on Supersymmetry and Unification of Fundamental Interactions, Lake Tahoe, CA, Aug. 2015

- S.W. Lee,
Recent Highlights of QCD: High-p_T Jet & V+Jets Production at LHC,
Plenary talk given at Experimental Challenges for the LHC Run II, Santa Barbara, CA, Mar. 2016

- S.W. Lee,
Recent Discoveries and Future Prospects at The Large Hadron Collider,
Invited public lecture, Phi Beta Kappa Honor Society, Lubbock, TX, Apr. 2016

- S. Undleeb,
Search for dark matter in monojet events in proton-proton collisions at 13 TeV,
Parallel talk given at American Physical Society April Meeting 2016, Salt Lake City, UT, Apr. 2016

- N. Akchurin,
Fast-timing Capabilities of Silicon Sensors for the CMS High-Granularity Calorimeter at the High-Luminosity LHC,
Plenary talk given at the XVIIth International Conference on Calorimetry in Particle Physics, Daegu, Korea, May 2016

- S.W. Lee,
Exotica Searches at CMS,
Plenary talk given at 2016 Mitchell Workshop on Collider and Dark Matter Physics, College Station, TX, May 2016

- J. Damgov,
Searches for Diboson Resonances with CMS,
Parallel talk given at Fourth Annual Large Hadron Collider Physics, Lund, Sweden, Jun. 2016