Final Report

Experimental Investigation of Hadron Collisions at the Highest Center-of-mass Energies

Experimental (CMS) Group
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Executive Summary

In this report, we summarize the research in physics of elementary particles conducted by the Florida Tech DOE supported group at the CMS experiment at CERN, during the last 3-year cycle under this grant. The personnel are listed under two teams led by each faculty:

1) Marc Baarmand (PI/PD, professor), Igor Vodopianov (research scientist) and graduate students Brian Dorney and Aiken Oliver.
2) Marcus Hohlmann (associate professor) and graduate students Himali Kalakhety, Mike Staib or Vallary Bhopatkar to be decided.

In addition several undergraduate students work in each team, supported by the Federal Work Study program at Florida Tech.

Baarmand's Team

As a charter member of the CMS experiment, Baarmand has been involved with its design, from RD5 days back in early 1990s, to its construction, commissioning and now data and physics analysis. After arriving at Florida Tech in 2000, Baarmand initiated a HEP program based on participation in CMS. Since 2003, DOE has provided base funding for this effort, which has grown substantially. In recognition of his accomplishments, Baarmand was the recipient of Florida Tech Faculty Excellence Award in Research and Florida Tech President's Award in 2009.

With project funds provided by US CMS, Baarmand and Vodopiyanov, who joined the team in 2002, designed and constructed a light (laser and LED) calibration and monitoring system for the CMS forward hadron (HF) calorimeters. Construction of the entire system was completed in fall 2005; the components were shipped to CERN for assembly and commissioning. Over the years, *Vodopiyanov has proven himself an indispensible member of the CMS hadron calorimeter (HCAL) community; his significant contributions to calorimetry have been recognized by the CMS management by assigning him the coordination of the HCAL Calibration group in 2011-12*. Each year in 2009-11, arranged by HCAL management and paid by USCMS funds, Vodopiyanov had an extended CERN visit of several months to work with the HCAL Detector Performance Group and Data Quality Monitoring. Vodopiyanov's work includes HCAL noise studies, calibration and timing, and performance during FY09-11 and continued obligations for FY12. In addition to the above tasks, Vodopiyanov has actively worked with our graduate students on the various physics analyses mentioned below. His main physics interest is in top quark spin and $t\bar{t}$ spin correlations, which he plans to start now that sufficiently large datasets are available.

The team has already produced two CMS PhDs, graduate students Hamit Mermerkaya (spin-spin correlation of top quark pairs) and Mike Ralich ($b\bar{b}$ angular and momentum correlations) completed their dissertations in fall 2009 and early spring 2010, respectively. Graduate student Dorney joined the team in fall 2009; he has had three productive years with significant contributions to two recent CMS B physics publication and analysis. Thanks to DOE base funds and US CMS project funds, Dorney is stationed at CERN to work as HCAL Operation Expert since October 2011 for a year, perhaps longer depending on availability of funds. His physics analysis work will also benefit from being at CERN and close contact with CMS physics conveners. Oliver is an incoming graduate student starting in spring 2012; he will be supported by Florida Tech as a graduate student assistant for the first year.

Since the arrival of $\sqrt{s}$ = 7 TeV physics data in 2010, Baarmand's team has used all available resources to do LHC physics analysis, as well as HCAL calibration and performance studies. *The work within the CMS B physics group has already produced one JHEP publication [i] with Baarmand and Dorney among the eight main authors. Our second analysis of* $b\,\bar{b}$ *correlations is based on events with muons and jets and the muon* p_T^{rel}. *We aim at completing this analysis for the winter conferences and soon after submit a CMS publication.* With the long data runs in 2011-12, physics analysis is priority number one. Future physics analysis possibilities include a search for low mass charged Higgs boson in decays of top quarks; inclusive search for resonances decaying into $b\,\bar{b}$, where we could benefit from methods developed in our $b\,\bar{b}$ correlation studies; and the study of top quark spin in $t\,\bar{t}$, which would be suitable for the incoming graduate student Oliver. *These physics topics would restart our Top physics activities as well as new work within the Higgs group, but require more DOE support for graduate students.* Because of active participation in CMS B physics, Baarmand was nominated for one of the convener positions in 2010. *Baarmand is currently a member of the CMS TOP physics publications Editorial Board, as well as a member of the CMS Authorship Committee.*

Hohlmann's Team

DOE OHEP has been supporting Hohlmann's CMS activities for six years. In FY09-11, Hohlmann's team contributed to the alignment of cathode strip chambers in the CMS muon endcap delivering final hardware-based alignment constants, to the Z′ search in the dimuon channel, and to initial R&D for a potential upgrade of the CMS forward muon system with Gas Electron Multiplier (GEM) chambers for tracking and triggering. The team operated and upgraded our CMS Tier-3 site T3_US_FIT on the Open Science Grid, which delivered ~500k CPU hours to CMS users and ~1M CPU hours to Grid users overall, and commissioned a Center for Tier-3 operations in our labs on campus. In June 2010, the Tier-3 site was reported by the CMS dashboard grid monitor as the "largest" CMS Tier-3 site in the world in terms of number of batch slots and TB of data storage available for Grid jobs. In 2010 and 2011, Hohlmann's team supported CSC operations with 22 shifts, central DQM with 34 shifts at the Fermilab ROC, and CMS GEM detector R&D with 17 test beam shifts at CERN.

One graduate student, Samir Guragain, received his Ph.D. in 2010 with a CMS dissertation and is now a CMS post-doc with Purdue U. (Calumet) at the Fermilab LPC. A second graduate student, Himali Kalakhety, became a Ph.D. candidate in spring 2011. In public outreach, Hohlmann was interviewed about the LHC startup in a 30-minute radio show that aired on three NPR stations in central Florida. He also provided technical support to local high school physics teachers and students for Quarknet. In 2011, Hohlmann received the 'Faculty Award for Excellence in Research' from the Florida Tech faculty senate for his work on CMS, computing, and GEM detectors.

In physics analysis, the Ph.D. candidate Kalakhety will continue his dissertation work on the Z′ search in the dimuon channel based on the full 2011/12 data set with the goal of graduating in mid-2013. We plan to help improve $t\,\bar{t}$ MC statistics for the Z′ search using the resources of our T3 cluster and will investigate the kinematics of the dimuon events to look for any anomalies. We will work with the CMS exotica resonance working group on setting limits on Z′ production based on the full 2011/12 data set.

1. Baarmand's Team

1.1. Introduction

The CMS experiment [ii] is designed to investigate physics of proton-proton collisions at a center-of-mass energy of 7-14 TeV at LHC operating at luminosities in excess of 10^{34} cm^{-2}s^{-1}. The physics program includes the study of electroweak symmetry breaking and search for the Higgs boson, investigation of the properties of heavy quarks, searches for new heavy gauge bosons, probing quark and lepton substructure, looking for supersymmetry and other phenomena beyond the Standard Model (SM). Baarmand's team physics interests in CMS are currently centered on three areas: The first area concerns Quantum Chromodynamics; *b* quark production provides an effective mechanism of testing perturbative QCD (pQCD). Measurement of the $b\ \bar{b}$ angular and momentum correlations, which examines the next-to-leading order component of the cross section, was the subject of Ralich's Ph.D. dissertation; Dorney has continued this work with an improved analysis using 2010 data and muon plus jets final states, it is nearly complete and expected to be approved by year end, see Section 1.3.1. A complimentary method for measurement of $b\ \bar{b}$ angular correlations, which is based on *b* quark identification using presence of secondary vertices in jets, allows for measurement of correlations down to small angles; the analysis is complete and published [i], see Section 1.2. As a major contributor to the CMS B physics, Baarmand organized a CMS B production workshop at Florida Tech on January 29-30, 2009.

The second area has to do with search for the SM Higgs boson in its decay into $b\ \bar{b}$. There is significant branching fraction in this mode for a low mass Higgs boson. However, it is a challenging decay mode in presence of large QCD backgrounds. After completing the present work on $b\ \bar{b}$ correlation measurement, we plan to use expertise learned to do an inclusive search for resonances decaying into a pair of *b* quarks. See Section 1.3.1. This may eventually lead to a Ph.D. dissertation for Dorney. The third area concerns top quark production and decay. The angular distributions of the top quark decay products allow determination of the top quark spin and search for possible deviations from the SM couplings. Measurement of the spin correlation in semileptonic $t\ \bar{t}$ events was the topic of Mermerkaya's Ph.D. dissertation; Vodopiyanov, who helped in setting up the analysis methodology after a similar analysis he had performed in 2006 [iii], is starting a new analysis that benefits from large 2011 datasets, see Section 1.3.2. Graduate student Oliver is also interested in working in top quark physics. The interest in top quark decays is in search for a charged Higgs. The Minimal Supersymmetric extension to Standard Model (MSSM) requires the introduction of two Higgs doublets in order to preserve the supersymmetry. There are five physical Higgs particles including two charged ones. Although not discussed in detail in this proposal due to page limitation, we do intend to recruit a new student to work on search for charged Higgs in top quark decays.

For CMS hadron calorimeters, Baarmand's team designed and constructed a light (laser and LED) calibration and monitoring system for the HF calorimeters. The details of the calibration system and its construction, commissioning and a selection of test beam results are described in [iv, v]. In Section 1.2, we present a brief review our major accomplishments in FY09-11, which include several important HCAL performance measurements, noise studies, timing and calibration work with collision data. In Section 1.3.3, we discuss our plans for continued participation in HCAL maintenance and operation, and obligations in calibration and performance studies in FY12 and beyond. Looking ahead and beyond the first few years of LHC operation, there are plans at CERN to upgrade the accelerator and increase its luminosity by a factor of 10, namely the Super LHC (SLHC). Consequently, the CMS detectors need to be upgraded to cope with the 5-fold increase in interactions per crossing. In Section 1.3.4, we briefly mention possible R&D areas of interest, which Baarmand's team will look into in order to extend our CMS hardware activities starting 2013.

In August 2009, Florida Tech was approved to receive $79,500 of ARRA funds, out of which $49,500 was allocated for Baarmand's HEP lab infrastructure improvements. The funds actually arrived at Florida Tech only in October 2010 and were used to upgrade our computing, to purchase equipment, and to complete a CMS Center. These improvements greatly enhance our computing power and lab facilities. It is also noteworthy that the installation and commissioning work were largely done by our undergraduate students supported by Federal Work Study program, i.e. at no cost to DOE. Appendix 1 describes our HEP facilities and the above infrastructure improvements.

1.2. Brief Review of FY09–11 Accomplishments

In this section we present the major accomplishments of the last 3-year funding cycle. In the following physics analyses, Baarmand and Vodopiyanov supervised the respective graduate students.

Top Quark Spin Study: The top quark decay occurs before either hadronization or depolarization can take place. This unique feature is used to investigate the spin of the top quark, where the angular distributions of the top quark decay products allow determination of the top quark spin. The spin correlation in the semileptonic $t\,\bar{t}$ channel (one W decay leptonically and the other hadronically) can be measured in terms of distribution:

$$\frac{1}{N}\frac{dN}{d\cos\phi} = \frac{1}{2}\left(1 - D\cos\phi\right), \qquad A_D = \frac{\sum_{i=1}^{3} A_i}{12} = \frac{D}{\kappa_1\kappa_2}.$$

The spin analyzer quality κ of the top quark daughter particle is defined as the degree to which the daughter particle is correlated with the top quark spin. The spin asymmetry coefficient A_D = 0.2, which was determined from the ALPGEN Monte Carlo [vi]. The analysis, documented in a CMS Analysis Note [vii], was approved by CMS and Mermerkaya presented it in a CMS Physics plenary meeting. The conclusion of the Monte Carlo study is that the spin asymmetry coefficient, in proton-proton collisions at 10 TeV and with a total integrated luminosity of 2 fb^{-1}, can be measured - the result is

$$A_D = 0.214 \pm 0.034\ (\mathrm{stat.})^{+0.040}_{-0.024}(\mathrm{sys.}).$$

***b* Quark Production Mechanisms:** In proton-proton collisions, *b* quark pairs are produced by three primary mechanisms, flavor creation (FC), flavor excitation (FE), and gluon splitting (GS). In the perturbative expansion of the $b\,\bar{b}$ production cross section (pQCD), FC accounts for the leading order (LO) and FE and GS account for the next-to-leading order (NLO). The correlations between *b* quarks are highly dependent on the production mechanism; two correlated variables are being used: Δϕ the opening angle between the quarks in the transverse plane and Δθ the difference between their polar angles. In order to identify two *b* jets from the jets passing the pre-selection in an event, a likelihood ratio (LR) method utilizing the SSV and pTrel *b* jet discriminators is used. An LR is formed for every jet pair combination in an event and the maximum LR is used to select the most likely *b* jet pair. To estimate the fractional contributions of the FC, FE, and GS subprocesses to the total $b\,\bar{b}$ production, the corresponding $\Delta\phi$ versus $\Delta\theta$ distributions from PYTHIA [viii] are fitted to the distribution of selected events after subtracting the background and correcting for the selection efficiency. The details of the analysis can be found in the CMS Analysis Note [ix]. It was approved by CMS and Ralich presented it in a CMS Physics plenary meeting. The conclusion of this Monte Carlo study is: From a muon plus jets event sample, collected in pp collisions at 10 TeV and corresponding to 8 pb^{-1} of integrated luminosity, the inclusive $b\,\bar{b}$ production mechanism fractions for events with $\hat{p}_T$ > 20 GeV can be estimated with overall relative uncertainties of less than 20% dominated by systematic uncertainties.

Angular Correlation of $b\,\bar{b}$ Quarks Based on Secondary Vertex: In collaboration with CMS colleagues from ETH-Zurich and University of Zurich, a new approach to identification of *b* quarks and selection of $b\,\bar{b}$ events was developed based on presence of a secondary vertex in *b* jets. This approach benefits from a secondary vertex algorithm, which can identify multiple secondary vertices in a jet independent of the jet reconstruction and allows for a first measurement of angular correlations down to small $b\,\bar{b}$ opening angles, e.g. pairs produced through gluon splitting subprocess. The analysis is based on data taken at √s = 7 TeV by CMS in 2010 and corresponds to an integrated luminosity of 3.1 pb^{-1}. The measured cross sections are shown in Fig. 1.2 as function of ΔR and $\Delta\phi$ for the three leading jet p_T bins. In conclusion, measurements of the angular correlations between BB pairs produced in pp collisions at √s = 7 TeV exhibit a substantial enhancement of the cross section at small ΔR and $\Delta\phi$, exceeding the values measured at large angular separation. The collinear region at small values of ΔR, where the gluon splitting is expected to be large, is not adequately described by any of the predictions. See [1] for details.

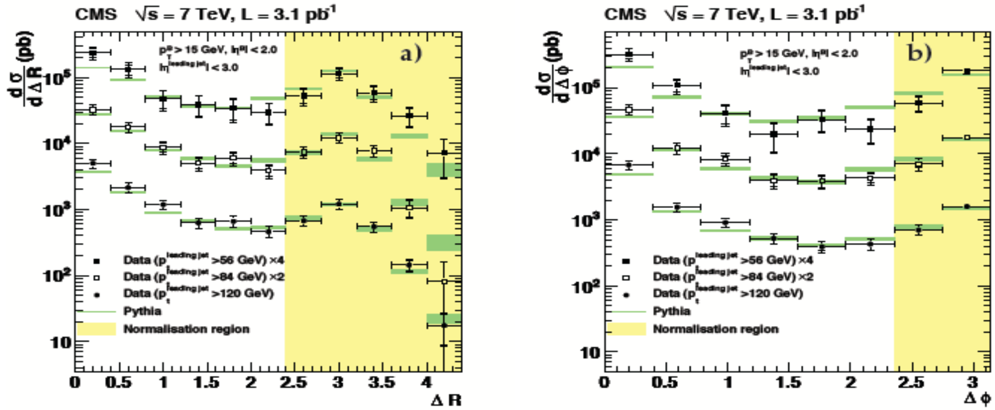

Fig. 1.2: Differential BB production cross sections as a function of a) ΔR and b) $\Delta\phi$ for the three leading jet p_T bins. For clarity, the $p_T > 56$ and 84 GeV bins are offset by a factor 4 and 2, respectively. For the data points, the error bars show the statistical and total errors. The PYTHIA simulation is normalized to the region ΔR > 2.4 and $\Delta\phi > 2.4$, respectively, as indicated by the shaded normalization regions.

CMS Detector Related Studies: Vodopiyanov has reported on HCAL noise studies, calibration, timing, diagnostics/ performance, operational decisions, and Software development in more than 80 presentations in many HCAL Detector Performance Group (DPG) meetings – below we give a summary of his major tasks. Beginning in 2011 Vodopiyanov coordinates the HCAL Calibration and Condition Tasks.

a) HF Diagnostics and Performance: Performance and stability of the HF readout channels were tested using the pedestal, calibration, special beam "splash" (taken with closed collimators) and collision data. Vodopiyanov combined different types of measurement that allowed identifying bad channels; leading to hardware repairs during LHC technical stops and calibration adjustments for some channels, see [x].

b) HF Timing: Precise reconstruction of the HF signal timing is important to understand the origin of the noise hits and elaborate noise filters. With the first beam data, it was shown that timing correction was necessary; optimal timing was estimated combining the collision data with Monte Carlo. Series of pp-collision runs with different HF phases were taken. Vodopiyanov derived the shape of the response pulse and time slew (dependence on amplitude) and modified the timing reconstruction code in the CMS software (CMSSW). Optimization helped to separate the signal and noise hits by timing, see Fig. 1.3.

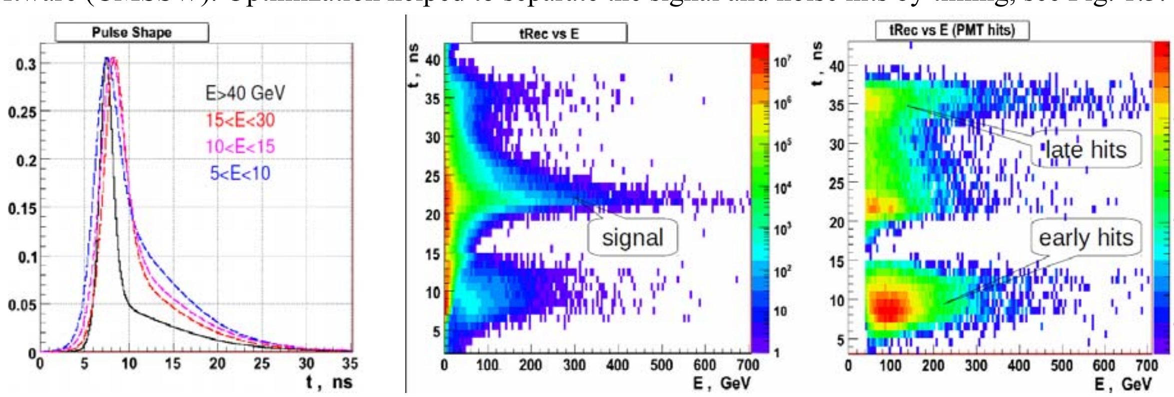

Fig. 1.3: Left: HF pulse shape derived for hits with different energies. Right: timing versus energy distributions for preselected signal and noise hits.

c) HF Noise Treatment: With start of pp-collision data taking in 2010, the HF noise rate was found to be significantly higher than expected, and the existing (software) noise filters were inefficient. Most of noise hits are attributed to the Cerenkov signals formed in PMT window by muons, which are expected to produce response coming earlier than the signal hits, Fig. 1.3. Other noise hits are scintillations in the light guides between PMT and HF absorber (late hits); they have a lower rate than the PMT window noise, but more energetic. Vodopiyanov contributed to development of advanced noise filters, which explore the topological and pulse shape algorithms [xi]. The topological one is based on expectation of a particle with energy greater than certain threshold to deposit energy in more than one calorimeter cell. The pulse shape filter rejects off-time and wide-pulse hits. The noise filters are implemented to the CMSSW, their performance is demonstrated in Fig. 1.4.

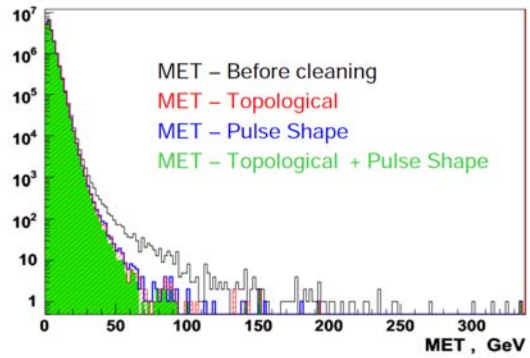

Fig. 1.4: Performance of the HF noise filters measured using the missing transverse energy distribution.

Vodopiyanov's detailed study of the noise hits allowed to make these recommendations for the HF noise treatment, which included both a short-term solution: using the noise filter and changing the light guides; and a long-term solution: changing of the HF PMTs. During the January-2011 technical stop, all light guides were replaced. Several PMTs of the new type were installed for testing. Work for the replacement of all HF PMTs is under way and is planned to occur in 2013. In 2011, Vodopiyanov made adjustments in the noise filters to account for the increased bunch crossing rate, 50ns. The topological noise filter is now implemented in the high level trigger. Regular adjustments of the noise filters are made.

d) HCAL Calibration: Initially HCAL was calibrated with radioactive source and by exposing several modules to test beam. Then, the calibration was improved using collision data by a relative scale adjustment in azimuthal angle (φ) based on the cylindrical symmetry of the calorimeter. Vodopiyanov developed an iterative algorithm, which used the responses of channels collected within certain optimal energy range. Corrections to the calibration coefficients were found in iterations, see Fig. 1.5, left. Comparison of the calibration corrections to those obtained with another method based on statistical moments (variance), is given in Fig. 1.5, right. The resulting corrections are estimated as error-weighted averages. Since introduced, Vodopiyanov's iterative method is used not only for calibration, but also in some diagnostics and validation tasks. Using the iterative method and changing the energy ranges, Vodopiyanov derived the energy-dependent correction functions and implemented them in the reconstruction code to compensate for the (effective) mis-calibration.

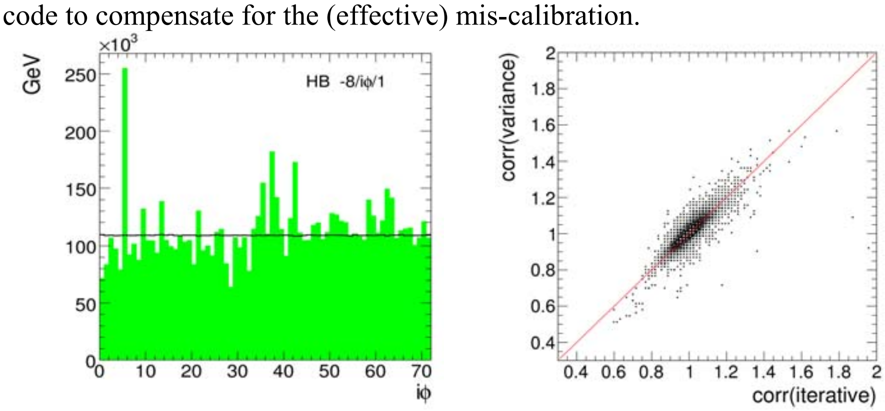

Fig. 1.5: Left: Energy depositions in one of the HCAL rings channels as function of their azimuthal index (green); black open histogram shows the depositions after correction. Right: Comparison of the

corrections to the HCAL calibration coefficients estimated using the variance and iterative methods obtained with the 2010 data; both sets of corrections have an RMS of about 0.1.

e) Coordination of the HCAL Calibration and Conditions Task: Starting in January 2011, Vodopiyanov took over the coordination of the *HCAL Calibration and Conditions Tasks*. This responsibility comprises of managing the task of continuously monitoring and improving the HCAL calibration, as well as maintenance of the HCAL *conditions*, which is a set of numeric files in the Data Base (including calibration constants) used for signal reconstruction. In 2011, besides the calibration work-flow, the Calibration and Operations groups performed special tasks for study and treatment of the HCAL barrel and endcap subdetectors (HBHE) readout instability. Gains of some photodiodes drifted (up or down) during 2011 by ~10%. After a series of tests, the procedure to resolve this issue was developed by Vodopiyanov. The *gain conditions* (factors converting digitized response to energy units) are now corrected using calibration runs monthly, and then performing ϕ-symmetry calibration on top of those corrections, then the *response correction conditions* are adjusted. The outcome was a set of validated HCAL calibrations, which was delivered for the 2011 data reprocessing at the end of the pp-collision run.

CMS Service and Outreach: The CMS authorship requirements have become increasingly more stringent. Each institution is now required to pledge and deliver a certain level of service work in CMS corresponding to their personnel size signing CMS publications. In 2009-11, Baarmand's team pledged and delivered 12-15 FTE months of service work each year in the following subtaskes: HF Detector Maintenance, HCAL P5 Shifts, Tool Development (noise filters, noise simulation, Calibration Methods, Reconstruction Code), Data Certification, Offline Software, Run Coordination (Central Shift leader and DQM) and HCAL Op Expert. Also, the team regularly does outreach activities to promote high energy particle physics in general, and LHC and CMS in particular.

2. Hohlmann's Team

2.1. Introduction

DOE OHEP has been supporting Hohlmann's CMS activities for six years. In the current FY09-11 cycle, DOE has been funding Hohlmann's team with an average of $53k annually in core support plus $30k of ARRA stimulus funding in 2010. This has covered one month of summer salary for Hohlmann, tuition and stipend for 1-2 graduate students, two months of post-doc support in FY11, limited travel, and ARRA capital equipment for Grid computing upgrades. For most of this period, Hohlmann has split his research efforts between CMS work and gaseous detector development efforts for the Dept. of Homeland Security. The DHS grant ended on 9/30/2011 and he is currently refocusing his funded research activities on CMS.

2.2. Review of FY09-11 Accomplishments

Alignment of Muon Endcap Chambers: In 2009-11, graduate students Samir Guragain and Himali Kalakhety produced a complete set of alignment constants for the ME ±2,3,4 muon endcaps using the laser and analog-sensor alignment system and delivered a corresponding database to CMS. The hardware-based alignment constants for axial coordinate z_{CMS} and the tilt angle $\varphi_{x\text{-local}}$ due to disk bending were combined with track-based alignment constants for the other four degrees of freedom into a final set of CMS alignment constants. This optimized the use of both alignment methods according to their respective highest sensitivities. A CMS paper describing results obtained with the muon hardware alignment system during CMS's first 'Cosmic Run At Four Tesla' (CRAFT) was published in the Journal of Instrumentation in 2010 [xii]. Guragain and Hohlmann had contributed the bulk of the material on the muon endcap analysis. G. Gomez (Santander) and Hohlmann had edited the paper jointly and had shepherded it through internal CMS reviews.

Physics with High-P_T Muons: Z′ Search in Dimuon Channel: Graduate student Samir Guragain defended his Ph.D. thesis on muon alignment and Z′ search in September 2010 and graduated in December 2010. For the physics section of his thesis he had studied the impact of systematic misalignments on the p_T resolution of endcap muons and on the achievable Z' signal significance in the dimuon channel [xiii,xiv]. Using the first 1.1 fb^{-1} of the 2011 data set, CMS officially updated its upper limits on the production ratio R_σ of cross section × BR into lepton pairs for Z′ production for the summer 2011 conferences. These limits exclude at 95% confidence level a Z'_{SSM} with standard-model-like couplings below 1780 GeV using only the dimuon channel (Fig. 2.1) and below 1940 GeV when combined with the dielectron channel [xv].

Kalakhety has continued our Z′ search effort with dimuons. In 2010, he attended the CERN-FNAL summer school on Hadron Collider Physics and a tutorial at the Fermilab LPC for training on the CMS Physics Analysis Toolkit (PAT). He is now producing PAT data sets for the $Z'\rightarrow\mu^+\mu^-$ analysis using the U. Florida T2 and our Florida Tech T3. Fig. 2.2 shows Kalakhety's preliminary analysis of the measured invariant dimuon mass using almost the entire 2011 CMS data set comprising 4.5 fb^{-1} of integrated luminosity compared to SM backgrounds from MC and to a hypothetical 1 TeV Z'_{SSM} signal simulated using MC. No excess signal over SM background is observed so far.

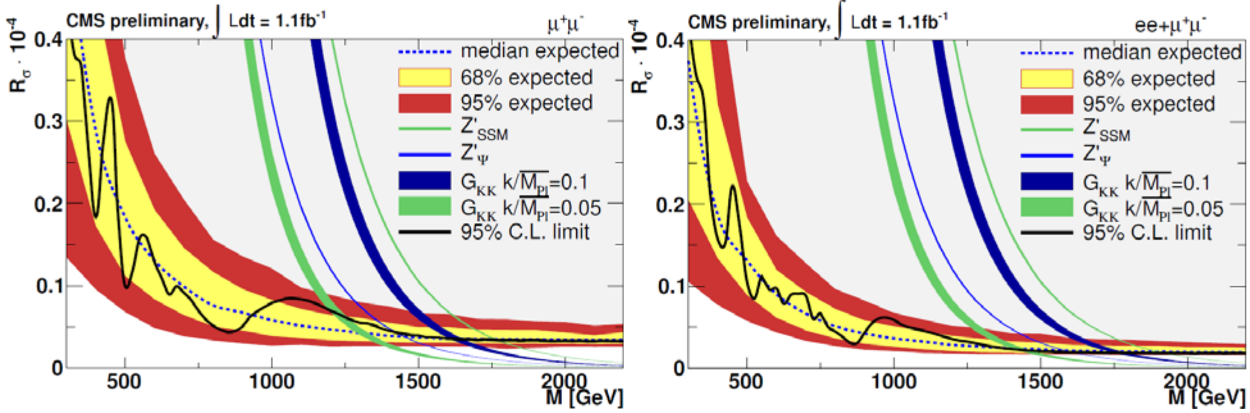

Fig. 2.1: Upper limits as a function of resonance mass M, on the production ratio R_σ of cross section times branching fraction into lepton pairs for Z'_{SSM}, Z'_Ψ, and G_{KK} graviton production using the first 1.1 fb^{-1} of the CMS 2011 data set for the $\mu^+\mu^-$ final state (left) and for the e^+e^- and $\mu^+\mu^-$ combined result (right). Predicted cross section ratios are shown as bands, with widths indicating theoretical uncertainties.

Operation and Expansion of Tier-3 Grid Site: Hohlmann's team of undergraduate students continued to operate and expand our CMS Tier-3 site FLTECH on the Open Science Grid (OSG). The site is presumably unique in that it was constructed and commissioned exclusively by undergraduates. Since Hohlmann organized a seminar with hands-on training sessions on Grid cluster administration for IT professionals from Florida Tech's IT department in summer 2010, we have been receiving limited help from the IT department in maintaining the Tier-3 site.

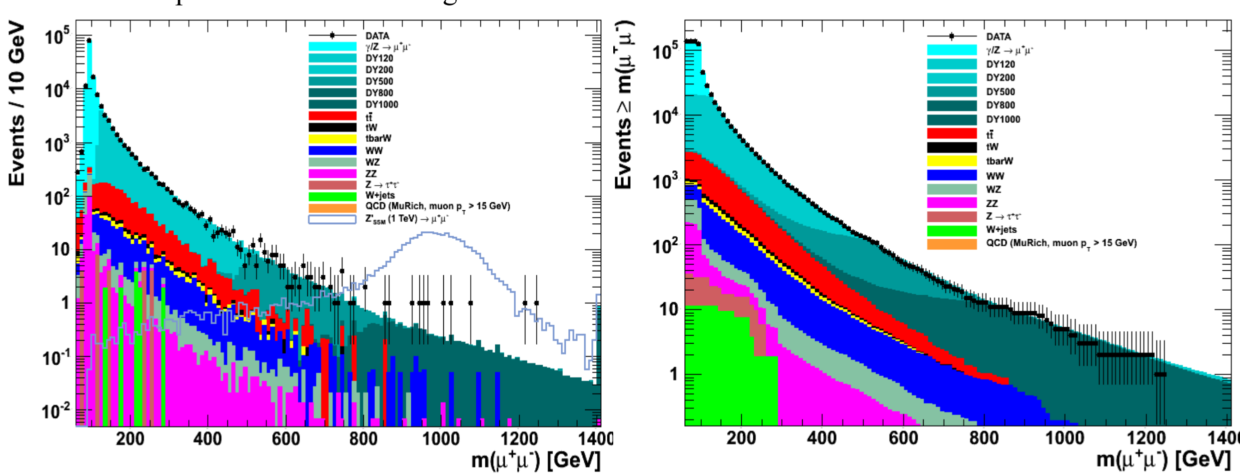

Fig. 2.2: Left: Preliminary dimuon mass distribution for 4.53 fb^{-1} integrated luminosity of CMS 2011 data compared with simulated background and Z' signal for $m_{Z'} = 1$ TeV/c^2. Right: Cumulative distribution.

The cluster has spent over 950,000 CPU hours so far on processing incoming Grid jobs during the current funding cycle with 490,000 CPU hours devoted to CMS analysis jobs; other main users were the Grid Lab of Wisconsin and OSG (Fig. 2.3 left). In June 2010, the FLTECH cluster was reported as the world's "largest" CMS T3 site by the CMS Dashboard (Fig. 2.3 right). Using DOE stimulus funding that arrived at Florida Tech in Sep 2010, we have enhanced our Grid operations. A 72 TB network-attached-storage element was installed that increases local storage capabilities for CMS data sets on the cluster by a factor of ~12. A center for Grid Operations has been set up by Hohlmann's students featuring several workstations, each with multiple screens that allow continuous monitoring of T3 Grid cluster operations, as well as of LHC and CMS status (Fig. 6.1, App.6).

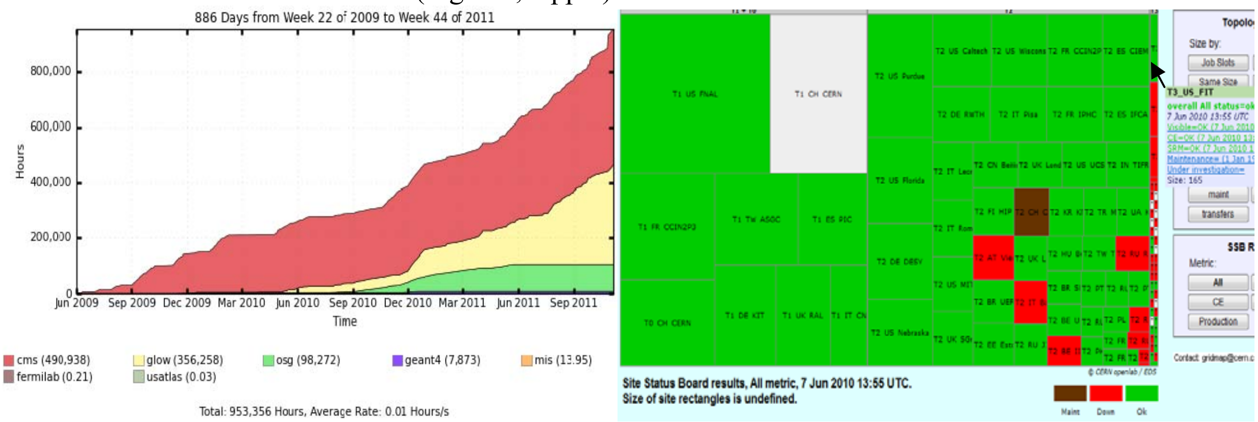

Fig. 2.3: Left: Cumulative CPU hours processed on the FLTECH Tier-3 Grid cluster from June '09 to Nov '11 for different virtual organizations (source: OSG). Right: Gridmap of CMS Grid site sizes from CMS dashboard monitoring tool. Rectangle sizes reflect site sizes as measured by number of batch slots plus number of TB of data storage available for Grid jobs. Colors reflect site availability. In this snapshot from 6/7/10, the Florida Tech site T3_US_FIT was the largest CMS Tier-3 site worldwide (black arrow).

R&D on GEM detectors for a CMS High-η Muon Upgrade: Recent progress with single-mask kapton etching techniques now allows the production of large Gas Electron Multiplier (GEM) foils. GEM detectors up to 1m×0.5m size have been produced by the GEM collaboration (GEMs for CMS) in cooperation with the CERN workshops and RD51, an international collaboration of 73 institutions hosted by CERN and dedicated to the development of Micro-Pattern Gas Detectors (MPGDs). Florida Tech is an RD51 charter member with Hohlmann as team leader.

Hohlmann's muon group has been participating in R&D for a proposed CMS hardware upgrade project since 2009. The objective is to instrument the $1.6 < |\eta| < 2.1$ region of the CMS muon endcaps with large-area GEM detectors to improve robustness of muon triggering and tracking in this region for the high rates at the high-luminosity LHC and the SLHC. The Florida Tech muon team is drawing on its experience with constructing and operating eight Triple-GEM detectors in a cosmic ray muon tracker from Hohlmann's DHS project. Hohlmann's team contributed seminally to a new "Scalable Readout System (SRS)," [xvi] which has been developed by RD51 specifically for MPGDs. The team developed online monitoring and analysis software for the SRS, was the first RD51 team to integrate the SRS with an MPGD, and spearheaded the commissioning of SRS hardware and software. CERN is currently in the process of commercializing the system through its tech-transfer department. We now routinely operate 8 Triple-GEM detectors with >12k SRS channels at 40 MHz sampling rate in the cosmic ray muon tracker [xvii] in our lab, which is currently the largest SRS implementation in existence. Students also developed a new cost-effective technique for thermally stretching GEM foils during detector assembly using infrared heating lamps [xviii]. This has the advantage that during assembly the sensitive detector components never have to leave the cleanroom for transportation to a large oven. Two 30cm×30cm Triple-GEM detectors with 1,500 channels each were constructed with this technique at Florida Tech and successfully operated [xix]. We also demonstrated that a large 1m×0.5m prototype drift foil for a CMS GEM detector can be successfully tensioned with our technique.

Hohlmann participated in the planning for construction and beam tests of the first full-size CMS high-η prototype detector at CERN in 2010 and contributed to the writing of two publications [xx,xxi] describing this effort. A second, full-size CMS high-η prototype detector with smaller spacing between GEM foils for improving time resolution was tested in several test beam efforts in 2011. Graduate student Mike Staib spent June 2011 at CERN to work on the beam test of this prototype in a high magnetic field. In August 2011, post-doc Kondo Gnanvo, who had previously worked on GEMs for the DHS project, was funded for two months on this grant to conduct a beam test of the prototype using the SRS. The use of analog front-end electronics allowed for the first multi-channel pulse height measurements of the large prototypes. This approach complemented previous measurements with VFAT2 electronics that use a binary readout with a programmable threshold. Gnanvo's data analysis using charge sharing between adjacent strips demonstrated for the first time that the CMS GEM prototype can achieve a spatial resolution of ~100µm at the narrow end of the trapezoidal chamber [xxii].

Hohlmann has helped to organize a proto-collaboration of CMS institutes interested in pursuing this CMS upgrade project, which constituted itself during the CMS week in March 2011 as the "GEM Collaboration (GEMs for CMS)". Currently he is serving as interim chair of the collaboration board and interim co-chair of the publications and conference board. This international proto-collaboration of currently 15 CMS institutions and 76 collaborators is in the process of producing a full Technical Proposal with the goal of submitting it to CMS management and collaboration boards and the LHCC in early 2012 to seek approval as an official CMS upgrade project. The project had already been briefly featured in an appendix to the currently endorsed Technical Proposal for the CMS upgrades.

Appendix 1:

Final ARRA Closeout Report

"RECOVERY ACT" - Experimental Investigation of Hadron Collisions at the Highest Center-of-mass Energies

Marc Baarmand, Marcus Hohlmann
Florida Institute of Technology, Melbourne, Florida
May 28, 2012

This is the closeout report for supplemental funds for research infrastructure for the Florida Tech DOE supported group under Grant # DE-FG02-03ER41264 through Funding Opportunity Announcement DE-PS02-09ER09-02. Our research program centers on the study of proton-proton collisions at a center-of-mass energy of 7-14 TeV at the Large Hadron Collider (LHC) particle accelerator located at the European Center for Particle Physics, CERN, in Geneva, Switzerland. Since 2010, data from these collisions are recorded using the Compact Muon Solenoid (CMS) experiment, which comprises a large system of state-of-the-art particle detectors.

The current personnel and CMS activities are listed under two tasks led by each faculty:

- Task A: Marc Baarmand (PD/PI, professor), Igor Vodopianov (research associate), Brian Dorney and Aiken Oliver (graduate students);
- Task B: Marcus Hohlmann (associate professor), Himali Kalakhety and Mike Staib (graduate students).

In addition several undergraduate students work in each subgroup. Our hardware responsibilities in CMS are with the hadron calorimeters, HCAL (Baarmand's group) and the endcap muon chambers, ME (Hohlmann's group).

As a one-time infrastructure improvement funds, Florida Tech was approved to receive $79,500 of ARRA funds in August 2009; the funds arrived at Florida Tech in October 2010. Baarmand's share of $49,500 was used for computers and other infrastructure needs, and Hohlmann's share of $30,000 was used for enhancing the Tier-3 grid cluster.

Task A – Baarmand
Approved expenditures:

$14k	Computers and peripherals.
$15k	A multi-channel digital scope.
$2.5k	A multi-channel-analyzer.
$18k	A conventional gas mixer system.
$49.5k	Total

Thanks to these funds we managed to modernize our computing and upgrade our lab infrastructure, which will help with our commitments to CMS and participation in its upgrade. We purchased 5 PC towers (Dell Precision T1500 8-core, 8GB RAM, 1TB hard-drive) with monitors and other peripherals, a laptop and a laser printer. These indeed modernized our computing power that will help a great deal with our CMS computing needs. We also purchased a webcam and a speaker phone to allow easy video conferencing with CERN and Fermilab. Several undergraduate work study students worked on bringing up these systems with the necessary OS (Windows, CERN SL5, Ubuntu) and other programs required for CMS software and analysis. Other lab equipment we purchased were: a multichannel analyzer with 2 μs dead time (ORTEC EASY-MCA-8K) including software with general spectrometric tools; a digital oscilloscope with analog bandwidth 2GHz and rise time 175 ps (LeCroy WAVERUNNER 620Zi) with two additional probes.

Benefits to HEP research

1- CMS Center at Florida Tech

The center provides a highly visible CMS focal point with several displays to check the status and monitor the CMS operations in real time. It will also allow for students, postdocs and faculty to work together at Florida Tech, as well as with other institutes and CERN using video links. Some of the typical activities are: subdetector data quality monitoring (DQM), calibration, event visualization and data analysis, computing operations, education and outreach. In addition, there is the possibility of doing remote shifts in future, e.g. offline DQM shifts.

The Florida Tech CMS Center is located in an annex (22×11 sq.ft.) to our lab, which has power, networking and lab benches for setting up the necessary computing consoles, with 2 PCs and 4 screens, allowing operation of 2 CMS functions concurrently. A large TV monitor can display a live feed from CERN that continuously shows a stream of important and interesting triggers. There are also important LHC and CMS pages and live TV that can be displayed. The video conference system can connect to the CMS centers at CERN, FNAL and others in CMS institutes using EVO. There are now permanent virtual rooms dedicated to CMS operations groups like Computing, Tracker, HCAL, ME, ECAL, etc.

The necessary web tools and browser to logon and operate the various CMS pages are: the DQM system for CMS detector data quality monitoring; Ci2i to manage CMS Center displays, users, groups, etc.; and CMS-TV for status displays and outreach. The PCs run Linux operating system SLC5 provided by CERN. The standard CMS software packages like CMSSW, Fireworks, iSPY and Iguana are installed, as well as Root and other physics analysis and grid packages. The entire setup and operation was done by undergraduate Federal work study students. Figure 1 shows the CMS Center located in the Olin Physical Sciences building.

Fig. 1: Florida Tech CMS Center located in the Olin Physical Sciences building.

2- Gas mixing station

A general-purpose gas mixing system suitable for many applications was constructed; thanks to Dorney's expertise and a lot of work by work study student Nick Guebert. A secure 15×20 sq.ft. area in the Olin

Physical Science high bay houses the station, next to a large heavy slab optical table, which can be used for placement of gaseous detectors. An existing PC is used to drive the gas mixing system.

The gas mixing station has 3 main components: gas piping, support and safety structures, and data acquisition system. The piping uses $1/4^{th}$ inch stainless steel pipes and connections (Swagelok). The gas from the tanks comes into the system through a regulator and where necessary a flash arrestor (Airgas), and into the solid piping system through high pressure rated metal hoses. The gas then flows through a diaphragm valve used on both ends to keep foreign objects out when the system is not in use. Each line of the system goes from their respective tank and valves to the mass flow controllers (Aalborg). The four mass flow controllers handle different flow rates (0-10, 0-50 and 0-100 ml/min) and are calibrated for isobutene, argon, and nitrogen. On the end side of the flow controllers there are a pressure gauge and a relief valve as a safety feature. The maximum pressure of the system will be 50 psig. For recalibration, a recalibration kit is purchased from Bubble-O-Meter. To meet the safety requirements, a gas detector displaying oxygen percentage (Grainger 2YA41) is used.

The Support structure (McMaster Caar) forms an upside-down T structure created from 80-20 slot frames with a sheet of aluminum to attach the components from the flow controllers and the valves. The flash arrestors have a rated working pressure of 50 psig and a pressure relief valve with 50 psig. The tanks are attached to the wall using a support and straps. Figure 2 shows the gas mixing station.

Fig. 2: The gas mixing station located in the Olin Physical Sciences high bay area.

The data acquisition is purchased from National Instruments. It is based on CDAQ-9174 (Compact DAQ chassis), which is the crate with the embedded interface controller. Several modules of the CDAQ-9174 standard, for control and monitor gas flow and temperature, are purchased as well. Lab View software (Florida Tech has a campus wide software license) is suitable for this hardware.

Task B – Hohlmann
Approved expenditures:

$13k	5 grid compute nodes with dual-quad core processors
$8.2k	1 network-attached storage element with 24TB of disk space
$2.6k	1 uninterruptible power supplies (UPS) with ~5kW power
$1.5k	1 Gigabit network switch, network cables, 1Gbit link for ext. network port (SE)
$1.7k	1 19" server rack for mounting new cluster elements
$1k	spare parts kits for nodes
$0.5k	upgrade of power infrastructure in physics high-bay
$1.5k	noise-reduction measures in physics high-bay
$30k	Total

Hohlmann's team of undergraduate students continued to operate and expand our CMS Tier-3 site on the Open Science Grid (OSG) during the ARRA grant period. The site is presumably unique in that it was constructed and commissioned exclusively by undergraduates. The cluster has spent over 1.1 million CPU hours on processing incoming Grid jobs during the ARRA funding cycle with 520,000 CPU hours devoted to CMS analysis jobs; other main users were the Grid Lab of Wisconsin and OSG (Fig. 2.3 Left). In June 2010, our T3_US_FIT cluster was reported as the world's "largest" CMS T3 site according to the CMS Dashboard (Fig. 2.3 Right).

Using the ARRA stimulus funding we have significantly enhanced our Grid operations. As we gained further experience with operating the cluster after submission of the proposal, it became clear that lack of mass storage was a more critical issue than lack of processing power. Consequently, a larger than originally planned network-attached storage element (NAS) with 72TB was procured and installed. The local storage capabilities for CMS data sets on the cluster were thus increased by a factor of ~12.

Effective facilities for day-to-day monitoring of the cluster operations were also sorely missing, which impeded our abilities to operate the cluster on the Grid and led to down times. A center for T3 Grid Operations was set up by Hohlmann's students in our HEP Lab A. Instead of procuring worker nodes for the cluster, a similar number of workstations were installed, each with multiple screens that allow continuous monitoring of T3 Grid cluster operation and of LHC and CMS status (Fig. 4). An undergraduate student developed a customized T3 cluster monitoring web page that is displayed on the main monitoring screen in the center and that automatically updates every 5 minutes. That page is visible on the big screen at the top of Fig.4. To be as cost-efficient as possible, these workstations were assembled from bare components by the students. The new center should also allow us to run CMS computing shifts directly from the center in the future.

Toward the end of the funding period, 10Gb networking equipment became more affordable and also the main link from campus to the internet was upgraded to 10Gb. We took advantage of these recent developments by procuring 10Gb networking equipment for the Compute Element, Storage Element, and 72TB NAS of the Grid cluster instead of the 1Gb equipment originally planned. This should reduce data transfer times to and from the cluster for Grid users. This is also the first instance of use of a 10Gb fiber connection to the Olin Physical Sciences building that houses our department and the T3 Grid cluster. As a welcome side effect, our efforts in Grid computing will thus be driving some campus IT infrastructure improvements. We will continue working with the IT Dept. to implement the 10Gb networking for the cluster. All computing and networking equipment described above was procured from US vendors.

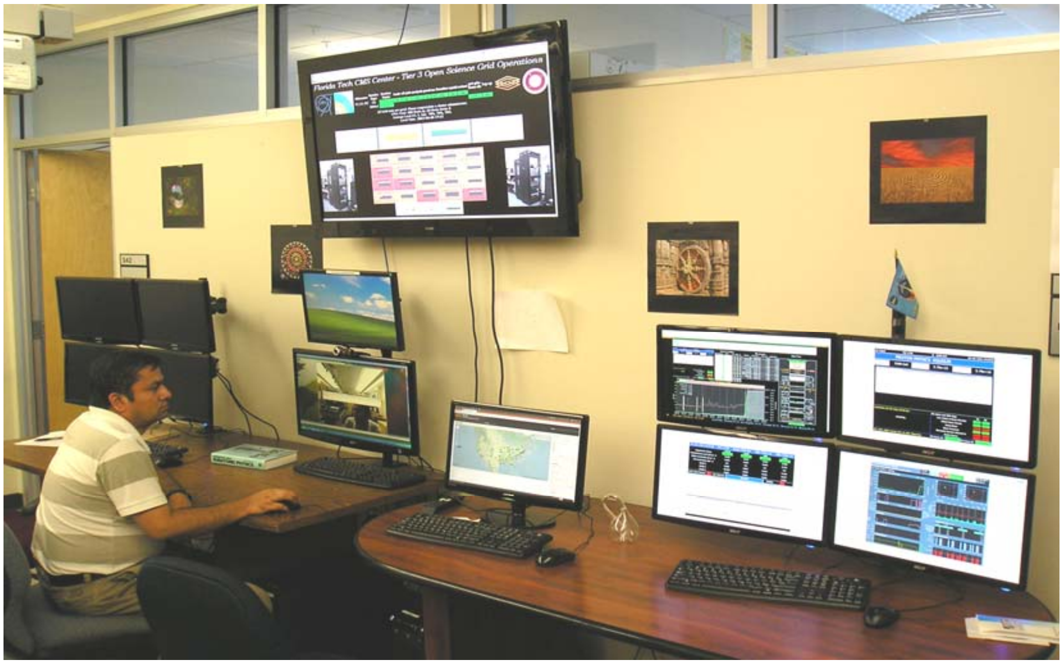

Fig. 4: Florida Tech Center for Tier-3 Open Science Grid Operations installed in 2011.

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