# FINAL REPORT
# TO THE U.S. DEPARTMENT OF ENERGY

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Report for period June 1, 2012 – March 31, 2015

*Experimental Group (CMS)*

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## Executive Summary

This final report summarizes activities of the Florida Tech High Energy Physics group supported by DOE under grant #DE-SC0008024 during the period June 2012 – March 2015. We focused on one of the main HEP research thrusts at the Energy Frontier by participating in the CMS experiment. We were exploiting the tremendous physics opportunities at the Large Hadron Collider (LHC) and prepared for physics at its planned extension, the High-Luminosity LHC. The effort comprised a physics component with analysis of data from the first LHC run and contributions to the CMS Phase-2 upgrades in the muon endcap system (EMU) for the High-Luminosity LHC.

The emphasis of our hardware work was the development of large-area Gas Electron Multipliers (GEMs) for the CMS forward muon upgrade. We built a production and testing site for such detectors at Florida Tech to complement future chamber production at CERN. The first full-scale CMS GE1/1 chamber prototype ever built outside of CERN was constructed at Florida Tech in summer 2013. We conducted two beam tests with GEM prototype chambers at CERN in 2012 and at FNAL in 2013 and reported the results at conferences and in publications.

Principal Investigator Hohlmann served as chair of the collaboration board of the CMS GEM collaboration and as co-coordinator of the GEM detector working group. He edited and authored sections of the detector chapter of the Technical Design Report (TDR) for the GEM muon upgrade, which was approved by the LHCC and the CERN Research Board in 2015. During the course of the TDR approval process, the GEM project was also established as an official subsystem of the muon system by the CMS muon institution board.

On the physics side, graduate student Kalakhety performed a Z' search in the dimuon channel with the 2011 and 2012 CMS datasets that utilized 20.6 $fb^{-1}$ of p-p collisions at $\sqrt{s}$ = 8 TeV. For the dimuon channel alone, the 95% CL lower limits obtained on the mass of a Z' resonance are 2770 GeV for a Z' with the same standard-model couplings as the Z boson. Our student team operated a Tier-3 cluster on the Open Science Grid (OSG) to support local CMS physics analysis and remote OSG activity.

As a service to the HEP community, Hohlmann participated in the Snowmass effort over the course of 2013. Specifically, he acted as a liaison for gaseous detectors between the Instrumentation Frontier and the Energy Frontier and contributed to five papers and reports submitted to the summer study.

## 1. Comparison of actual accomplishments with goals and objectives of the project

As outlined in the 2011 project proposal, the team planned to focus its hardware efforts fully on R&D for a CMS high-η muon upgrade with GEM detectors. We had proposed a long-term program of developing a production and testing site for CMS high-η GEM detectors at Florida Tech to complement future chamber production at CERN. For FY12, we proposed to produce and test a first GE1/1 muon endcap prototype GEM chamber in our facilities. We planned to contribute to the development of software for adapting the RD51 Scalable Readout System to the VFAT2 chip for use in GEM chamber R&D. The group also planned on participating in 2012 beam tests of GEM prototype chambers at CERN. For FY 13 & 14, we proposed the continuous development of our chamber production and testing site based on the lessons learned in FY12. In addition to technical work, Hohlmann planned to continue on with managerial responsibilities as interim chair of the collaboration board of the "GEM collaboration (GEMs for CMS) " that had formed around the CMS high-η muon upgrade effort. In particular, the P.I. intended to work closely with the project manager, Archana Sharma (CERN), and the management board of the GEM collaboration to prepare a formal technical proposal for submission to the CMS CB and to the LHCC by early 2012.

Most of the objectives listed above were accomplished. The chamber production and testing site was put in place. We participated in the 2012 beam test of GEM prototype chambers at CERN and reported the results in a presentation and proceedings of the IEEE 2012 Nuclear Science Symposium. The first full-scale CMS GE1/1 chamber prototype built outside of CERN was constructed at Florida Tech after some delay in summer 2013. We continued our development of economical GEM readouts with zigzag strips as an R&D effort to reduce channel numbers and hence cost for large-area GEM detectors. We mounted a beam test for full-scale CMS GE1/1 chamber prototype with both standard and zigzag readout strips at the FNAL test beam facility in fall 2013. The test results were reported in a presentation and proceedings for the IEEE 2014 Nuclear Science Symposium and in a NIM publication. Hohlmann continued as chair of the collaboration board of the CMS GEM collaboration and as co-coordinator of the GEM detector working group until summer 2015. He served as editor and main author of the chapter that describes the GE1/1 GEM detector design in the technical design report (TDR) for the muon endcap GEM upgrade, and as language editor for the whole document. The TDR was approved by the LHCC and the CERN Research Board in 2015. During the course of the TDR approval process, the GEM project was also established as an official subsystem of the muon system alongside CSCs, DT, and RPCs by the CMS muon institution board.

The originally planned effort on developing software for adapting the RD51 Scalable Readout System (SRS) to the VFAT2 chip was abandoned because the GEM collaboration decided to focus the SRS usage only on the APV chip for chamber quality control purposes while independently developing directly the final CMS DAQ system for the VFAT2/3 chips.

In physics analysis, Ph.D. candidate Kalakhety was to 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 planned to help improve $t\bar{t}$ MC statistics for the Z′ search using the resources of our T3 cluster and to investigate the kinematics of the dimuon events to look for any anomalies. We were going to work with the CMS exotica resonance working group on setting limits on Z′ production based on the full 2011/12 data set. This program was completed as planned albeit with a bit of delay; Kalakhety graduated in December 2014.

## 2. Summary of project activities

### 2.a. GEM detectors for CMS muon upgrade

**Overview:** A group of gaseous-detector experts within CMS co-led by Hohlmann has been pioneering large GEM detectors [i,ii,iii,iv,v,vi] in cooperation with the CERN workshops and RD51, an R&D collaboration of ~75 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 group has been participating in the CMS GEM effort since the very beginning of the R&D phase in 2009 and was the first U.S. group to engage in this effort. CMS management had approved a first formal CMS R&D effort (CMS RD10.02) proposed by Beijing, CERN, Gent, Florida Tech, Frascati, and Pisa in 2010. Hohlmann helped to build a larger collaboration of CMS institutes, which constituted itself during the CMS week in March 2011, to pursue this GEM upgrade project. Since formation, Hohlmann has been serving as chair of the board of the CMS GEM collaboration, which currently comprises 40 CMS institutions including five U.S. institutions (Florida Tech, Texas A&M, UCLA, U. Florida, Wayne State). In 2009-12, Hohlmann served as co-chair of the internal publications and conference board of the GEM collaboration.

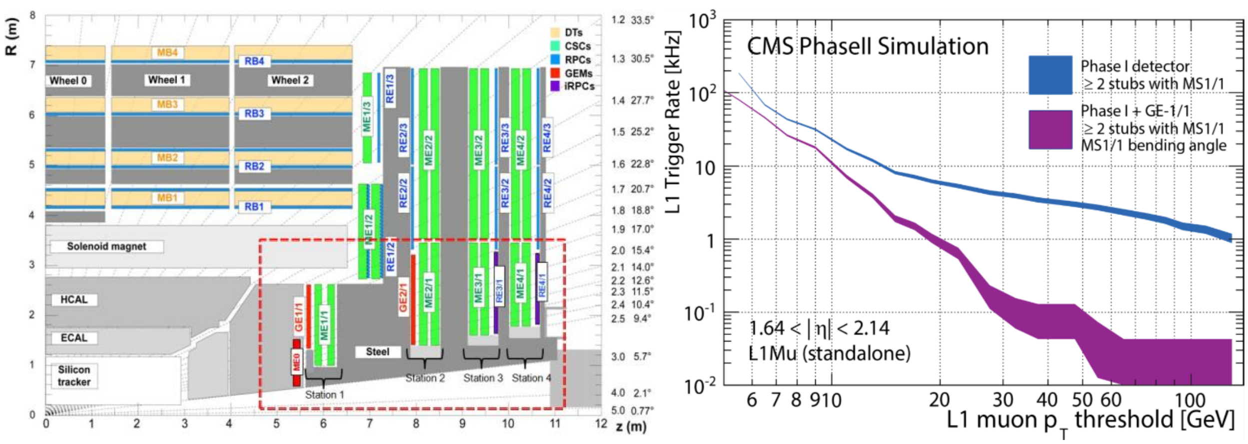


**Figure 1.1:** *Left:* Quadrant of CMS with proposed muon system upgrade in the red rectangle. New forward-muon GEM stations are indicated in red (ME0, GE1/1, and GE2/1). *Right:* Expected L1 muon trigger rates at 14 TeV and L = 2 × $10^{34}$ $cm^{-2}$ $s^{-1}$ with (purple) and without (blue) GE1/1 at a pile-up of 50 [vii].

In 2012, the collaboration submitted technical proposals [vii,viii] on upgrading the inner ring of the first muon endcap station with a GEM subdetector system (GE1/1) to CMS management. Hohlmann served as a main editor of these proposals. This prompted an internal CMS review by a committee led by G. Apollinari (FNAL) in spring 2013. In this review, Hohlmann presented the GEM technology choice for the proposed upgrade. As a result of the review, CMS management subsequently approved a so-called slice test with several GE1/1 chambers and close-to-final electronics to be installed in CMS in the 2016 year-end shutdown of the LHC. From September 2013 to August 2015, Hohlmann co-convened the GEM chamber working group of the GEM collaboration with L. Benussi (Frascati). The initial main goal of the CMS GEM collaboration is the installation of a full GE1/1 system in the second long shutdown of the LHC (LS2).

In summer 2014, the GEM collaboration was recognized as a full-fledged subgroup of the CMS muon institution board alongside the drift tube (DT), resistive plate chambers (RPC), and cathode strip chamber (CSC) communities. CMS formulated its overall plans for the LHC Phase-2 in a technical proposal that was presented to the LHCC. The muon section of this TP proposes an upgrade of the muon endcap with three GEM subdetector systems. In addition to the GE1/1 station, a corresponding GE2/1 station is proposed for the second muon endcap station, and a so-called ME0 station is envisioned behind the upgraded endcap calorimeter for tagging muons up to $|\eta|=3$ (fig.1.1). The CMS GEM collaboration prepared a technical design report (TDR) [ix] focused on the GE1/1 project which was approved by LHCC and the CERN Research Board in 2015. Hohlmann was a member of the TDR editorial board with particular responsibility for the chapter on design and performance of GE1/1 chambers.

**Technical GEM Developments at Florida Tech:** The first full-scale CMS GE1/1 prototype chamber ever built outside of CERN was constructed at Florida Tech in summer 2013. Using parts procured from CERN under this grant, our students assembled a trapezoidal GE1/1 with opening angle of 10° and dimensions 990 mm × (220-455) mm in our cleanroom and and then commissioned it with x-rays in our chamber irradiation facility. With an eye towards GE2/1 development, we also designed a new readout board with radial zigzag strips for this prototype to reduce channel numbers and consequently cost for large-area GEMs. This readout board is segmented into 8 η-sectors with 128 radial zigzag readout strips per sector and was built by industry. The angular strip pitch is 1.37mrad, the pitch between two tips in the same strip is 0.5mm and the closest distance between tips in neighbouring strips is ~0.1mm (fig.1.2).

Students transported the CMS GE1/1 prototype detector to Fermilab in October 2013 for a three-week test in the MT6.2 beam line at the FNAL test beam facility. The detector could be equipped with either the standard CERN readout board with 3,072 straight radial strips or with our zigzag-strip readout board that uses only 1,024 radial zigzag strips to read out the entire active region (fig.1.2). Students also brought several small GEM detectors to the beam test. Florida Tech and U. Virginia operated ten GEM detectors with Ar/$CO_2$ 70:30 in a tracking configuration with four small reference GEM detectors in fixed positions for beam tracking and six probed detectors mounted on a motion stage for position scans (fig.1.3). We collected over 3 million triggered track events, mostly with secondary hadron beams of 20-32 GeV energy. This beam test constitutes the most comprehensive performance study of a GE1/1 prototype to-date.

All detectors were read out with APV hybrids that sample pulse heights on 128 strips at 40 MHz. Eight APV hybrid chips suffice to fully read out the zigzag GE1/1 detector (fig.1.3) while the regular CMS readout requires 24 APVs. The zigzag design saves 2/3 of the channels and corresponding electronics cost.

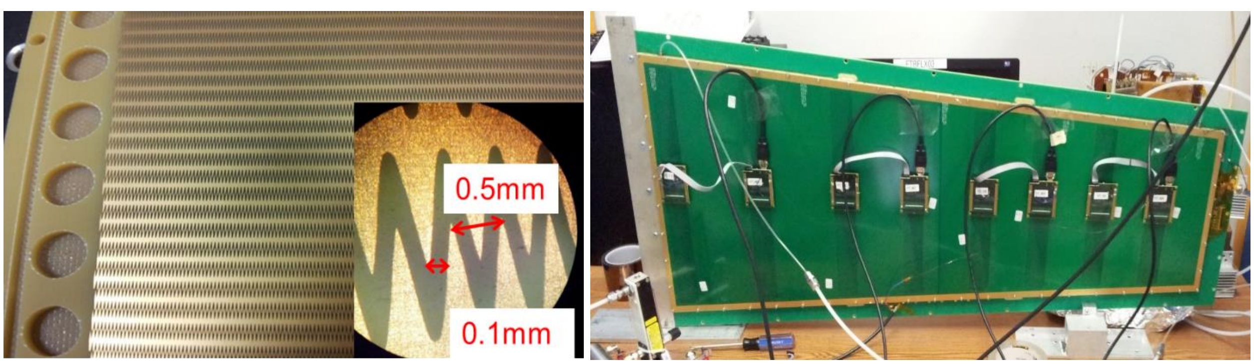


**Figure 1.2:** *Left:* Photo of the printed circuit readout board with zigzag strips with a microscope picture of the zigzag structure in the inset. *Right:* Trapezoidal GE1/1 chamber with 3/1/2/1mm foil gaps and zigzag pcb fully instrumented with only 8 APV hybrids. Four HDMI cables (black) read out the entire chamber.

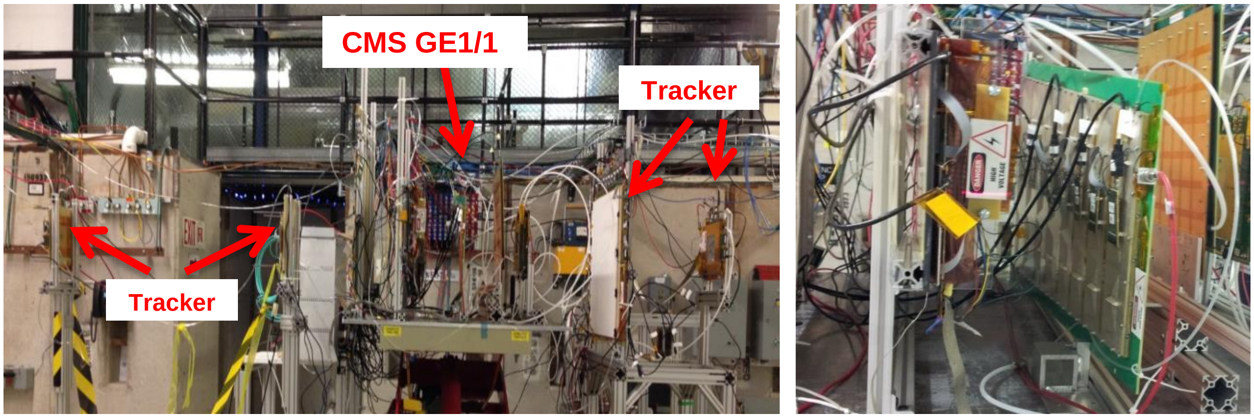


**Figure 1.3:** *Left:* CMS GE1/1 prototype detector in FNAL MT6.2 beam line. *Right:* Close-up of GE1/1 prototype with one of three rows of straight readout strips instrumented with eight APV amplifier hybrids.

Using beam test data, we studied the performance of the GE1/1 chamber with both readout strip types. The measured plateau detection efficiency of (98.4 ± 0.2)% with the zigzag GEM detector in mixed hadron beams is fairly insensitive to the threshold cut applied to the measured strip charge to define a hit on a strip (fig.1.4). On the efficiency plateau, the strip multiplicity of the zigzag strip clusters is dominated by clusters with two and three strips (fig.1.4). With the straight-strip readout, the angular resolution of the GE1/1 prototype is 123 µrad on the efficiency plateau above 3200V. This is to be compared with a resolution of 137 µrad that was measured with straight-strip readout and binary readout electronics (VFAT chips) at a CERN beam test in 2012 [iv]. For the three-times-coarser zigzag readout structure, the resolution is measured to be about 180 µrad on the efficiency plateau for 2-strip and 3-strip cluster after response corrections. If clusters with all strip multiplicities are used, i.e. when hits with single zigzag strips are also included, the resolution ranges from 180-240 µrad on the efficiency plateau (fig.1.5) as the fraction of hits with single zigzag strips drops with increasing HV (fig.1.4). We concluded that it is that a GE1/1 with zigzag-strip readout can achieve similar angular resolution as with the reference straight-strip readout but with three times fewer channels and hence at considerably lower cost.

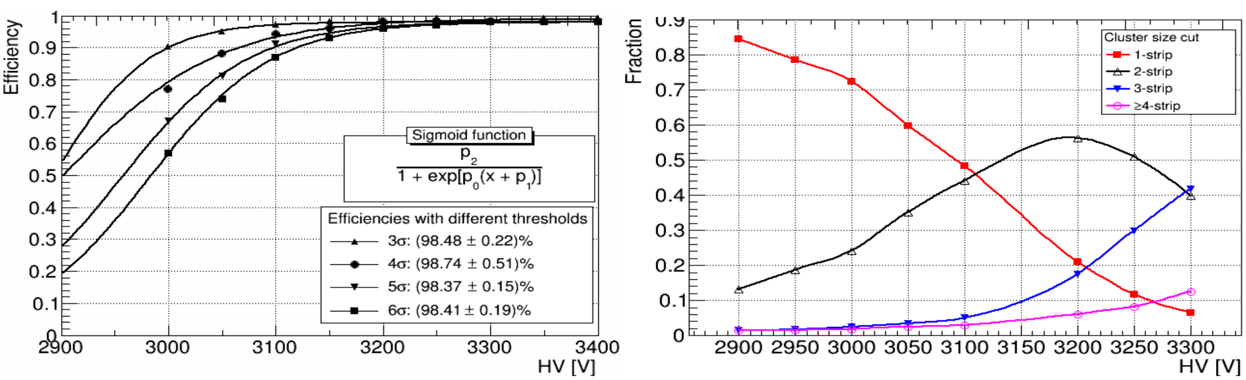


**Figure 1.4:** *Left:* Detection efficiency vs. $HV_{drift}$ for different cuts on the pedestal width. *Right:* Strip cluster size vs. $HV_{drift}$ in central η-sector. Statistical errors are smaller than markers.

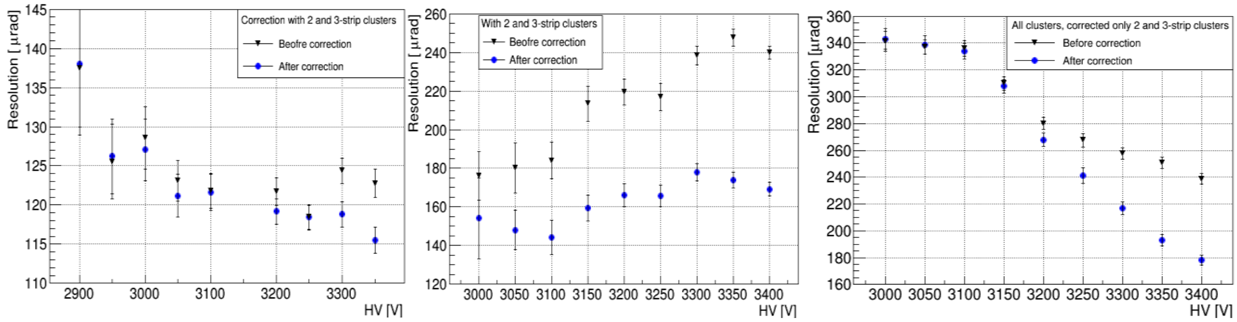


**Figure 1.5:** Measured angular resolutions for 2-strip and 3-strip clusters vs. $HV_{drift}$ in central sector 5 of the GE1/1 before and after strip response corrections for straight-strip (*left*) and zigzag-strip (*center*) readouts, as well as for all strip clusters for the zigzag readout (*right*).

**GE1/1 Production Site Development:** We have developed a GE1/1 chamber production and commissioning site at Florida Tech. The CMS GEM collaboration was developing several such sites at Bari, CERN, Fl. Tech, Frascati, Gent, and India. The CERN and Fl. Tech sites are currently the most advanced sites. Our site is housed in a high-bay experimental area within our department (fig.1.6). It features a 200 sqft. clean room tent (class 100-1000) with a large optical table that allows simultaneous assembly of two GE1/1 detectors, a class 10 flow-hood for GEM stack assembly under cleanest conditions, and a large Plexiglas box for leakage current measurements of GEM foils under $N_2$ flow. Directly adjacent to the cleanroom we have set up a 1,000 sqft. GEM commissioning lab with a 5'×7' shielding box (fig.1.6) that allows full-body x-ray irradiation of short and long GE1/1 chambers to test their response uniformity. We have installed a dedicated RD51 SRS DAQ system with 4k channels that allows readout of an entire GE1/1 chamber with APV hybrids. Undergraduates in our group have also refurbished a table-top electromagnet with 10 cm diameter pole faces that can reach a magnetic field just above 1T and they mapped the field.


**Figure 1.6:** Left: GEM production and commissioning site at Fl. Tech. The clean room tent is visible in the background. Right: Test stand with x-ray generator on left and GE1/1 on right inside large shielding box.

## 2.b. Physics with High-$P_T$ Muon

Graduate student Kalakhety finished his analysis work on the Z' search in the dimuon channel with the 2011 and 2012 CMS datasets. He completed and defended his Ph.D. thesis on this topic in December

2014. CMS results from a combination of 2011 data with partial data from the 2012 run appeared as a journal publication in March 2013 [x].The final Z' search utilizes 20.6 $fb^{-1}$ of p-p collisions at $\sqrt{s}$ = 8 TeV recorded in 2012 with the CMS detector. In the analysis, the reconstructed dimuon invariant mass spectrum is compared to SM expectations (fig.1.8). Since no significant excess is found, we set upper limits on the ratio $R_\sigma$ of the cross section times branching ratio for the decay of any new Z' boson to the known cross section times branching ratio for the Z boson at the 95% confidence level (fig.1.7) using a Bayesian approach. For the dimuon channel alone, the 95% CL lower limits on the mass of a Z' resonance are 2770 GeV for $Z'_{SSM}$ and 2430 GeV for $Z'_\psi$ (fig. 1.8) [xi]. When combined with results from the sister analysis in the dielectron channel, limits increase to 2960 GeV and 2600 GeV [xii], respectively.

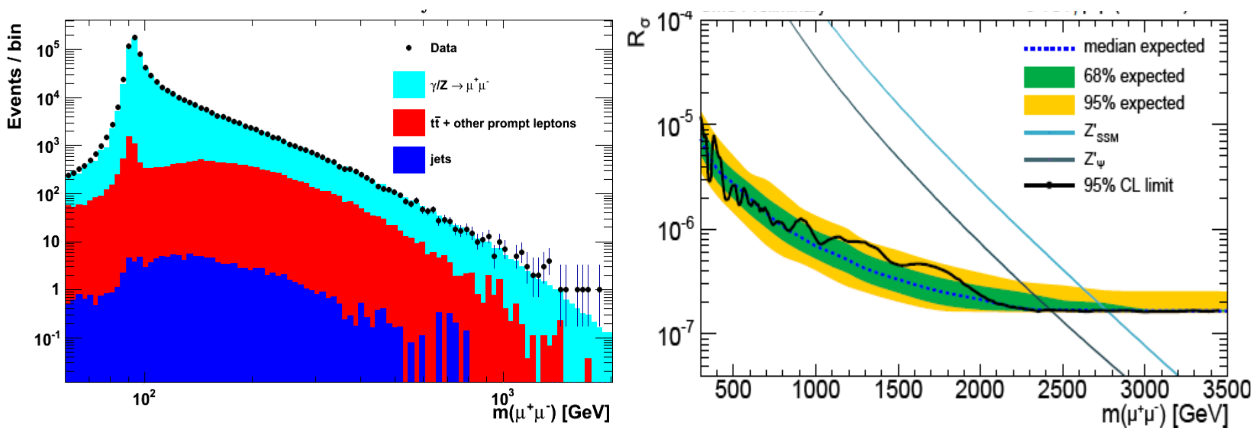


**Figure 1.7:** *Left:* Kalakhety's observed opposite-sign dimuon invariant mass spectrum overlaid on the background prediction for 20.6 $fb^{-1}$ of 2012 data. *Right:* Resulting upper limit on the ratio $R_\sigma$ of $\sigma \times$ BR into dimuon pairs for Z' production to the same quantity for Z production vs. resonance $\mu^+\mu^-$ mass. The predicted $\sigma \times$ BR ratios for $Z'_{SSM}$ and $Z'_\psi$ are shown as bands with widths indicating theoretical uncertainties.

### 2.c. Operation of Tier-3 Grid Site

Hohlmann's team of undergraduate and graduate students continued to operate, maintain, and improve our CMS Tier-3 site FLTECH on the Open Science Grid (OSG). The site is presumably unique in that it was originally constructed and commissioned exclusively by undergraduates. In 2014, for example, the cluster spent over 700,000 CPU hours processing incoming Grid jobs. Experience gained with the system administration of our Grid cluster helped graduate student Jordan Robertson land a computing internship at NASA Goddard Center in summer 2013. This turned into a full-time position for him after graduation in May 2014.

### 2.d. Service to HEP community and Educational Effort

Per invitation from the conveners of the Coordinating Panel for Advanced Detectors (CPAD) of the APS DPF and of the Instrumentation Frontier (InF) study group for the *2013 Snowmass Community Summer Study* [xiii], Hohlmann participated in the Snowmass effort over the course of 2013. Specifically, he acted as a liaison between the InF and the Energy Frontier (EF) for gaseous detectors. With the InF group, he attended a number of preparatory conference calls, the initial workshops at Argonne and Boulder and the main event at Minnesota. Hohlmann initiated the participation by colleagues from nuclear physics in the InF study to explore potential synergies between future HEP and NP detector R&D for the Snowmass process.

Hohlmann contributed to five papers and reports submitted to the summer study. He is the single author of a white paper on the prospects of using 3D-printing technology for detector development and production [xiv] and first author of a white paper on status and future R&D directions for MPGD's in tracking and muon detectors [xv]; both are cited in the final Snowmass report. He co-authored a companion white paper on prospects for MPGD use in calorimeters [xvi] and contributed a section on future muon detectors to the summary paper [xvii] of the energy frontier working group within the larger Instrumentation Frontier. Much of the material from the MPGD muon and tracking white paper was used in the overall summary report of the Instrumentation Frontier [xviii] in the context of the need for R&D on pixelated detectors.

With respect to GEM commercialization efforts in the U.S., Hohlmann is founding member of an informal task force comprising colleagues from Brookhaven, Stony Brook, Temple, U. Virginia, and Yale, that meets biweekly with representatives from TechEtch, the only U.S. company that has signed a GEM licensing agreement with CERN, and the leader of the CERN workshop that makes GEM foils. The objective is to facilitate full technology transfer of single-mask GEM foil production technology from CERN to TechEtch so that a domestic source of large-area GEM foils for the HEP community can be established. Currently, CERN is still the only place in the world that can produce large-area GEM foils. In 2014, TechEtch produced its first single-mask GEM foils. The quality of their small-size (10cm × 10cm) and medium-size (30cm × 40cm) foils is very high in terms of uniformity of hole diameters and hole pitches [xix].

On the educational side, we are helping to organize hands-on exercises for the first CMS detector school to be held at DESY in November 2014. We are making actual GEM data from the FNAL testbeam and analysis scripts available to participants. Two graduate students attended a CMS data analysis school at FNAL. Hohlmann facilitated DOE-INFN summer internships for two undergraduates in our group at Frascati in 2013 and 2014 through his CMS GEM contacts there. Both undergraduates also traveled to CERN during that period to work on large-GEM assembly or to participate in a CMS GEM workshop.

### 2.e. Other activities

DOE had instructed a rapid phase out of support for research scientist Igor Vodopiyanov, who had been working with Marc Baarmand, P.I. of the previous DOE HEP grant at Fl. Tech. Vodopiyanov's grant support was terminated on Oct 31, 2012. Ph.D. student Brian Dorney, who worked with Baarmand, received some supplemental funding under this grant for supporting CMS HCAL operations and run coordination at CERN in 2012.

## 3. Products developed under the award

### 3.a. Publications (in chronological order)

1. D. Abbaneo, et al. (CMS GEM coll.), “Beam Test Results for New Full-scale GEM Prototypes for a Future Upgrade of the CMS High-eta Muon System,” Proc. 2012 IEEE Nucl. Sci. Symp., N14-137, Anaheim, CA, arXiv:1211.3939.
2. CMS Collaboration, “Search for heavy narrow dilepton resonances in pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV,” Phys. Lett. B 720 (2013) 63.
3. M. Hohlmann, V. Polychronakos, A. White, and J. Yu, "Micro-Pattern Gas Detectors for Charged-Particle Tracking and Muon Detection," Proc. of 2013 APS-DPF Snowmass Community Summer Study, SNOW13-00025, arXiv:1306.1924 [physics.ins-det], June 8, 2013.
4. U. Heintz, D. Bortoletto, M. Hohlmann, T. LeCompte, R. Lipton, M. Narain, and A. White, "Instrumentation for the Energy Frontier," Summary paper by the energy frontier working group within the instrumentation frontier, Proc. of 2013 APS-DPF Snowmass Community Summer Study, SNOW13-00141, arXiv:1309.0162 [physics.ins-det], Aug 31, 2013.
5. M. Hohlmann, "Printing out Particle Detectors with 3D-Printers - a Potentially Transformational Advance for HEP Instrumentation," Proc. of 2013 APS-DPF Snowmass Community Summer Study, SNOW13-00137, arXiv:1309.0842, Sep 3, 2013.
6. J. Yu, M. Hohlmann, V. Polychronakos, and A. White, "Micro-Pattern Gas Detectors for Calorimetry," one-pager white paper, in Compendium of Instr. Frontier Whitepapers on Technologies for Snowmass 2013, FERMILAB-FN-0971-PPD, Sep 2013.
7. M. Demarteau, et al., "Planning the Future of U.S. Particle Physics (Snowmass 2013) - Chapter 8: Instrumentation Frontier," Conveners' report for APS-DPF Snowmass Community Summer Study, FERMILAB-CONF-13-648; SLAC-PUB-15960; arXiv:1401.6116, Jan 2014.
8. V. Bhopatkar, M. Hohlmann with D. Abbaneo et al., "Performance of a Large-Area GEM Detector Prototype for the Upgrade of the CMS Muon Endcap System," Proc. 2014 IEEE Nucl. Sci. Symp., Seattle, WA, arXiv:1412.0228.

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[i] D. Abbaneo, et al. (CMS GEM coll.), “Characterization of GEM Detectors for Application in the CMS Muon Detection System,” Proc. 2010 IEEE Nucl. Sci. Symp., Knoxville, TN, arXiv:1012.3675, RD51-NOTE-2010-005.

[ii] D. Abbaneo, et al. (CMS GEM coll.), “Construction of the first full-size GEM-based prototype for the CMS high-η muon system,” Proc. 2010 IEEE Nucl. Sci. Symp., Knoxville, TN, arXiv:1012.1524.

[iii] D. Abbaneo, et al. (CMS GEM coll.), “An overview of the design, construction and performance of large area triple-GEM prototypes for future upgrades of the CMS forward muon system,” JINST 7 (2012) C05008.

[iv] D. Abbaneo, et al. (CMS GEM coll.), “Beam Test Results for New Full-scale GEM Prototypes for a Future Upgrade of the CMS High-eta Muon System,” Proc. 2012 IEEE Nucl. Sci. Symp., N14-137, Anaheim, CA, arXiv:1211.3939.

[v] D. Abbaneo, et al. (CMS GEM coll.), “The status of the GEM project for CMS high-η muon system,” Nucl. Instrum. Meth. A732 (2013) 203-207.

[vi] D. Abbaneo, et al. (CMS GEM coll.), “Upgrade of the CMS Muon System with Triple-GEM detectors,” Proc. of INSTR2014, Novosibirsk (2014).

[vii] D. Abbaneo, et al., “Technical Proposal – A GEM Detector System for an Upgrade of the CMS Muon Endcaps,” CMS IN 2012/001 (2012).

[viii] CMS GEM Coll., “A GEM Detector System for an Upgrade of the High-η Muon Endcap Stations GE1/1 + ME1/1 in CMS,” Internal LS2 Project Proposal – based on CMS RD 10.12 (2012).
[ix] CMS Coll., “CMS Technical Design Report for the Muon Endcap Upgrade: GE1/1 – The Station 1 GEM Project,” CERN-LHCC-2015-012, CMS-TDR-013, ISBN 978-92-9083-396-3.
[x] CMS Collaboration, “Search for heavy narrow dilepton resonances in pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV,” Phys. Lett. B 720 (2013) 63.
[xi] G. Alverson, et al. “Search for High Mass Resonances Decaying to Muon Pairs in pp Collisions at $\sqrt{s}$ = 8 TeV,” CMS AN 12-422 (2013).
[xii] CMS Coll., “Search for Narrow Resonances in Dilepton Mass Spectra in pp Collisions at $\sqrt{s}$ = 8 TeV,” CMS Physics Analysis Summary EXO-12-061 (2013).
[xiii] J. Rosner, M. Peskin, and N. Graf (eds.), “2013 Community Summer Study on the Future of U.S. Particle Physics (Snowmass 2013)”; FERMILAB-CONF-13-648; SLAC-PUB-15960 (2013).
[xiv] M. Hohlmann, “Printing out Particle Detectors with 3D-Printers, a Potentially Transformational Advance for HEP Instrumentation,” Proc. 2013 Snowmass Community Summer Study, SNOW13-00137, arXiv:1309.0842 (2013).
[xv] M. Hohlmann, V. Polychronakos, A. White, J. Yu, “Micro-Pattern Gas Detectors for Charged-Particle Tracking and Muon Detection,” Proc. 2013 Snowmass Community Summer Study, SNOW13-00025, arXiv:1306.1924 (2013).
[xvi] J. Yu, M. Hohlmann, V. Polychronakos, A. White, “Micro-Pattern Gas Detectors for Calorimetry,” in H. Frisch, et al., “Compendium of Instrumentation Frontier Whitepapers on Technologies for Snowmass 2013,” FERMILAB-FN-0971-PPD (2013).
[xvii] U. Heintz, D. Bortoletto, M. Hohlmann, T. LeCompte, R. Lipton, M. Narain, A. White, “Instrumentation for the Energy Frontier,” Proc. 2013 Snowmass Community Summer Study, SNOW13-00141, arXiv:1309.0162 (2013).
[xviii] M. Demarteau, et al., “Instrumentation Frontier Report,” Ch.8 in [15].
[xix] B. Surrow, “Test and characterization of commercially produced GEM foils using single-mask techniques,” Presentation, RD51 mini-week, June 2014, https://indico.cern.ch/event/323839.