Final Progress Report
and a request for supplemental funding

April 1, 2013 - April 30, 2016

1. DOE award: SAP Grant #50201774, Sponsor Award #DE-SC0010157

Name of recipient: Lawrence R. Sulak
Institution: Boston University, Organizational DUNS 049435266

2. Project Title: "Exploring High Energy Interactions with CMS at the LHC"

Name of the lead PI: Lawrence R. Sulak
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Abstract:
This High Energy Physics research project achieved its goal of exploring high-energy interactions with 7, 8 and 13 TeV data accumulated by CMS at the Energy Frontier. For the original hadron calorimeter (HCAL) and for its upgrade during Long Shutdown 1 (LS1), the PI helped propose and implement the upgrading the phototubes, new electronics, and fast timing of the hadronic forward (HF) and hadronic outer (HO) calorimeters of CMS, projects which he had forcefully advocated since the inception of CMS. The PI and his colleagues Prof. J. Rohlf and chief electronics engineer E. Hazen, his post-docs A. Heister and S. Girgis, and his graduate students (P. Lawson and D. Arcaro) contributed software tools used in perfecting of μTCA and Advanced Mezzanine Card (AMC13) electronics, the PC board that provides clock, timing and DAQ service for HCAL (and now many other subdetectors and central systems in the upgraded CMS detector). This Task reaped the benefits of these hardware contributions 1) to hermiticity for missing energy searches, and 2) to forward tagging jets for Vector Boson Fusion processes by analyzing and publishing early data, including that for the Higgs discovery and for exotic and supersymmetric searches.

3. Date of the report: August 1, 2016
Period covered by the report: April 31, 2013 to April 30, 2016

4. Accomplishments of this DOE task over the full 3-year budget period

4.a) Roles of the PI:

Over the period of this 3-year grant, in recognition of the PI's contributions to the physics dependent upon the hadron calorimeter, the PI has served in several advisory and upgrade positions, boards and committees of the CMS Hadron Calorimeter Subsystem. He was chosen by both CMS and ATLAS to present their combined results on *"Jet Production and Properties at Hadron Colliders"* at the IXth Latin American Symposium on High Energy Physics. He worked full-time for 4 months in residence at CERN each summer, as he has since 2003, despite only 1 month of salary support, for the first time, during this 3-year grant.

The PI's involvement in Hadron Calorimetry (HCAL) at the LHC dates from before the inception of the CMS collaboration. Upon the cancellation the SSC, he brought to CMS the technology and prototypes for the forward quartz-fiber Cherenkov calorimeter, which he had developed for the GEM detector at the SSC, and has been deeply involved with HCAL since the beginning of CMS.

The achievement of goals of the forward sub detector of HCAL has been amply demonstrated over the last three years. They are two-fold:

a) Providing complete hermiticity up to eta = 5, critical to searches beyond the standard model using missing energy, *e.g.* supersymmetry, and

b) Tagging two jets, one in each of the forward calorimeters, forward and backward, to study the vector boson fusion production mechanism of the Higgs, to search for strong WW scattering, and to look for higher mass Higgs states. This role was central in the discovery of the Higgs boson, and continues to be important in the detailed study of it properties.

CMS papers to which the PI has contributed to in this reporting period reflect the efficacy of the detector he initiated, help design, prototyped, has aided in maintenance, and is now assisting in both Phase 1 and Phase 2 Upgrades.

The PI's collaborators acknowledged his current contributions to CMS by electing him as the following:

i) Chairman for 2013-14 of the US CMS HCAL Institution Board.

Jeff Spalding and Didier Contrado, CMS Upgrade Managers early in FY14, has him serve on their
ii) CMS Upgrade Steering Committee, and

iii) on the Committee that drafted the US CMS Upgrade LOI.

Slawek Tkaczyk, as CMS Hadron Calorimeter Upgrade Coordinator, gave him the responsibility of serving on the
iv) HCAL Upgrade 1 Implementation Committee.

Pawel de Barbaro, Hadronic Calorimeter Project Manager, uses the PI on his
v) CMS HCAL Advisory Panel, a group of only 5.

A major challenge in FY15 &16 has been evaluating the radiation damage to the HCAL Endcap Calorimeter (HEE) and determining a solution to it. Jim Freeman, Vasken Hagopian, Andris Skuja (chair), and the PI are the senior participants in the
vi) HEE Radiation Damage Task Force, which is charged with determining the upgrade options to solve it.

BU's HCAL electronics contributions are substantial, *e.g.* initially the Data Control and Concentrator (DCC) PC card. During this funding period we proposed, and CMS adopted the μTCA and the AMC13 standards, replacing VME.

In FY2015 and 16 the PI's main responsibilities were as critic of the CMS HCAL Phase 2 Upgrade, vetting the options for

1) redesigning the HCAL Endcap calorimeter, whose radiation damage is worse than anticipated, and is not predicted to survive beyond Long Shutdown 2 (LS2). The PI served on the Radiation Damage Task Force, with J. Freeman and A. Skuja.

2) upgrading the front end of the current hadronic endcap calorimeter's electronics component (HEE).

This required evaluating two competing technologies:

a) a shashlik liquid-filled fiber calorimeter, which has had significant prototyping, but the danger of leaks, *etc.* Having been a lead institution in the MACRO experiment, we at BU are well qualified to critique liquid scintillator detectors, *vs*.

b) a high-density digital calorimeter (HGC) based on silicon, which is an expensive and novel technology, but the realization of an electronic calorimeter. BU has had significant experience developing this technique for the ILC.

Upon evaluation of both, the collaboration decided last year, with input from this Task, to take the HGC route, where the PI plays a consultative role.

Working on Upgrade Electronics with Grad Student Arcaro and Post-Doc Girgis

For the last 3 years the PI has been guiding his graduate student, Dan Arcaro, in furthering the past hardware work (and analysis) of his previous PhD student, Phil Lawson, who was already on the grant at the start the FY13-15 period. Arcaro is also assuming tasks of Dr. Arno Heister, the PIs former post doc/assistant research professor. As an assistant to Eric Hazen, our electronics engineer, Arcaro became responsible for our μTCA software tools for the CMS Upgrade. Arcaro is now fully operational as a resident at CERN, and is taking over from Jim Rohlf's student, David Zou, who will be returning to BU shortly.

To have an eventual successor to Arcaro, when he returns from CERN in a year, the PI recruited Dr. Semiray Girgis, a new postdoctoral fellow, to the BU CMS group in FY16. She had been working on CMS HCAL for 4 years with the PIs long time collaborator, Dr. Slawek Tkaczyk, a Fermilab Senior Scientist in residence at CERN. This task benefited greatly from Girgis's presence at BU while she assimilated basic electronics from the PI and learned everything she could from Arcaro before he left for CERN. Her portfolio now includes developing software tools for supporting μTCA electronics and for its commissioning. (Since we have insufficient DOE funds to support her, she is independently funded in the short term.)

Analyzing Jet Data with Tkaczyk (Fermilab) and Arcaro

While pursuing his HCAL hardware contributions CMS, the PI has championed analyses using the data from the forward calorimeter, primarily for the missing energy signature for SUSY and for the forward tagging jets for the vector boson fusion production channel of the Higgs. As a member of the latter analysis group, he helped prepare the Analysis Note that led to that seminal paper. With Phil Lawson, he completed a paper on jets (Lawson's PhD on this topic).

This current analysis effort (see below) has been greatly enhanced over the last three years by working in close collaboration with Tkaczyk. He and the PI have been guiding Arcaro in the physics analysis for his PhD, with the goal of measuring Drell-Yan production, and potentially strong WW scattering, using data from the forward calorimeter. Outside of the 4 months each summer when the PI is resident at CERN, Tkaczyk serves as the local CERN co-thesis advisor.

4. b) CMS Upgrade electronics accomplishments Arcaro

Arcaro has contributed substantially to the Phase 1 AMC13 and μTCA Upgrade. The currently μTCA at CERN is fully capable of taking over the entire HCAL system, replacing the old VME electronics. The μTCA Upgrade is performing identically to the legacy electronics, but has both more spare parts and more

technical support. The current data rate is far less than its bandwidth capabilities, and with the completion of multi-DAQ commissioning, the system will be able to handle the data rate after Phase 2 Upgrade as well. Testing of this will start in September 2016.

Here are the technical details of the accomplishments of Arcaro during the 3 years of this grant:

Parsing the AMC13 data format

The introduction of the μTCA electronics at the beginning of Phase 1 required a new raw data format as compared with the previous VME electronics output. Arcaro wrote the software to break down the new output of the AMC13. This enabled us to parse generated events in our test stand at BU to study the AMC13 behavior at varying rates and event sizes.

He used C++ to write the base classes of the code in a way that mirrors the data format. This makes it easy to build C++ tools to extract any information from the data utilizing those base classes. His first tool is a general-purpose data quality check of the data. It calculates a cyclic redundancy check (CRC) for an event and verifies that it matches the CRC in the data format.

Arcaro then used ROOT to build histograms of the bunch crossing and orbit numbers to confirm the trigger and timing control (TTC) inputs were working properly. He generated large sets of events using varying trigger rates and event sizes and confirmed key data elements, such as matches of event number throughout the data. This method is now the first test of new firmware before it is released for use at CERN.

Reprogramming with the AMC13 flash tool

Arcaro's main AMC13 software project was rebuilding a flash-programming tool to enhance its capabilities and to have it as a standalone program. If either of the two AMC13s firmwares (called T1 and T2) becomes corrupted, the main AMC13 tool cannot resolve the disagreement: the connection relies on both T1 and T2. Formerly this required using a programming cable, which is not optimal if failures occur during LHC collisions. The reprogramming operation now only requires a connection to the T2; he rebuilt the relevant AMC13 C++ classes to require just the T2. This new tool connects to the AMC13 through the T2 and reprograms any firmware even when the more susceptible T1 is corrupt. Because of its convenience and independence from the main software, the tool is now the main option for programming, even if neither firmware is corrupted.

Commissioning multiple optical outputs

Arcaro, working with Colin Jacob (another graduate student the PI has been training for CMS) updated the AMC13 software to handle multiple optical outputs (multi-DAQ). The multi-DAQ enables two or three of the fiber outputs, increasing the data throughput of the card in the same proportion. This increases the data flow capability to ~30 Gbps, which will be necessary after the 2016 Extended Year End Technical Stop (EYETS) when HCAL will be more finely segmented increasing the number of channels by a factor of ~3.

Incorporating FEROL cards and testing multiple optical output functions

At BU in 2016 we incorporated two Front-End Readout Optical Links (FEROL), the first components of the CMS DAQ, into our test stand and commissioned multi-DAQ. The AMC13 sends the data to the FEROL. With the Upgrade setup, we both read off events in the AMC13 memory using Arcaro's newly developed software and look at the event from the FEROL's end. He adapted his parsing software to handle the modified FEROL format and CMS can now made direct comparisons to verify that the two data outputs agree.

After Arcaro moved to full-time residence at CERN, he modified the test stand at Building 904 to handle the new outputs. This involved adapting the HCAL software to include the changes in the AMC13 classes to read out the new format. This is currently functioning for small-sized events, and will soon be stress tested at high rates and data sizes. The goal is to measure the upper limits of the data rate capability with multi-DAQ. This limit is key in determining how HF will handle zero suppression after EYETS. Without zero suppression, the data rate may surpass the AMC13 limit. We will have FEROLs to test from full production runs in September 2016.

AMC13 recovery and maintenance

During Phase 1 Upgrade we have installed ~50 μTCA crates for the entire Hadron Calorimeter (of a total of ~200 crates) with each housing an AMC13. This number of cards requires constant expert work to recover malfunctioning cards and to solve new problems that have not been seen on the test stands. During June 2016 one group noticed that a heat sink on an AMC13 slid off the main FPGA because it had an incorrect adhesive. We found that 4 other AMC13s in HCAL were in the same production batch and likely to have the same problem. We then disassembled the affected AMC13s and replaced the heat sink during LHC downtime.

Upgrading first batch of AMC13s with new chips

The initial production of ~45 AMC13s used an FPGA that was later upgraded to improve performance. This batch performs adequately; however it had hardware specific bugs. We produced replacement T2 boards with upgraded FPGAs to solve this. We rebuilt the old AMC13 cards with the new chip to have the cards identical to the new production of cards. Arcaro programmed and tested each of the new T2 boards and ran them through stress tests in the test stand at Building 904 at CERN. These boards are now either used at 904 in the newer μTCA crates or at P5 as production spares.

Checking firmware version number

In a one incident, multiple μTCA crates needed to be completely restarted. An AMC13 in one of the crates had reverted to an earlier version of the firmware. The HCAL software did not have any method of validating the AMC13 firmware; Arcaro created a check to run during the configuration of the board. At the beginning of each run, the software now reads the firmware version number from each AMC13 and verifies that it is the proper version. If any AMC13 fails this test, the run will not start; instead it logs that one of the cards has an unexpected version. Since the addition this check, we found that the same AMC13 reverted to an older firmware again, and fixed it before any LHC collisions.

Serving as DAQ electronics expert on call

For a week each month Arcaro is on-call as the HCAL data acquisition expert; he assist the shifter with any problems during data taking. This involved learning the alarms coming from electronics other than the AMC13, such as the μHTRs (HCAL Trigger board) and the low and high voltage systems. This is critical to reducing HCAL data loss during collisions.

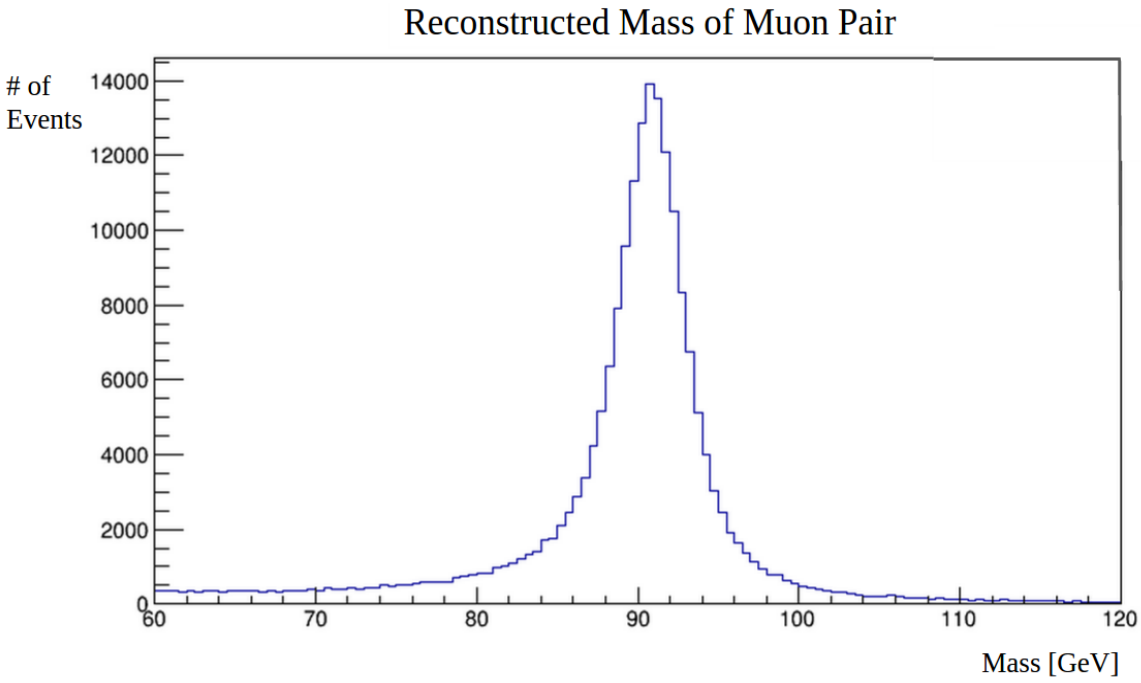
Testing "New Generation" electronics for Phase 2 Upgrade

Relative to "new generation" (ng) electronics, Arcaro has been helping to set up production level test stands. All the μTCA electronics is now operational as well as a few fully functional front-end readout boxes (others are being assembled). Arcaro is responsible for keeping the AMC13 cards running, up to date, and able to satisfy the needs of the ng hardware. With FEROLs arriving in September, full production testing of the ng front-end electronics will begin.

4. c) Analyzing physics data with Arcaro and Tkaczyk

Drell - Yan at 13 TeV and comparison with new NNLO calculations

In his first two years of this grant, Arcaro became proficient with C++ and CMS Software (CMSSW). He learned how to extract physics analysis objects, such as muons from data, and to form plots of energy, p_t, *etc.* He has been studying two muon final states decaying from a Z boson. This involves applying selection cuts for muons variables to increase signal to background at the Z mass. Below is one of his histograms, the reconstructed mass from the double muon 2016 sample ~5 fb^{-1} of data, after his selection cuts have been applied. The mean and width agree well with the particle data group values for the Z boson.



The production of Higgs and of supersymmetric particles has significant background contributions from the Z-boson decay. To correct for these backgrounds the theoretical model of Drell and Yan must be c to calculated to high accuracy. In Run 1, CMS used a next-to-leading order model to correct for this background. In Run 2, with higher energies, an improved model is necessary to extract new particle signatures and Higgs signals from the LHC data.

Recent theoretical work on the Drell-Yan process and Z boson production has improved corrections from NLO [1] to next-to-next leading order (NNLO, or third order) with five partons. CMS has analyzed data [2] taken at 7 and 8 TeV incorporating the NNLO correction [3], but we have yet to compare the prediction with the experimental data from Run 2 at the LHC. The theory calculations at 13 TeV [4] produce significant corrections to the current Drell-Yan background in simulations. We aim to make this comparison.

Tkaczyk, Arcaro, and the PI have initiated collaboration with Dr. E. Barberis (NEU, co-convenor), Ph. Gras (CEA), and L. Favar (Bruxelles) of the Standard Model Physics-Vector boson plus Jet (SMP-VJ) group. Our intent is to adopt the group's analysis framework so that ours can easily be double-checked.

Arcaro is familiarizing himself with their event selection and will incorporate it into his analysis to compare results with the latest theory. He is using the MC samples generated by the SMP group to validate his event selection and to approximate backgrounds in the data sample. We also plan to collaborate with K. Rabbertz (Karlsruhe) to open another analysis route for measuring particle distribution functions.

1. W. T. Giele, E. W. N. Glover and D. A. Kosower, Nucl. Phys. B 403, 633 (1993).
2. S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 722 (2013) 238 [arXiv:1301.1646 [hep-ex]]; Phys. Rev. D 88 (2013) 11, 112009 [arXiv:1310.3082 [hep-ex]]. V. Khachatryan et al. [CMS Collaboration], Phys. Rev. D 91 (2015) 5, 052008 [arXiv:1408.3104 [hep-ex]].
3. A. G. D. Ridder, T. Gehrmann, E. W. N. Glover, A. Huss and T. A. Morgan, arXiv:1507.02850 [hep-ph].
4. R. Boughezal et al Phys. Rev. Lett. 116, 152001 (2016).

4. d) CMS Upgrade hardware & software work with Semiray Girgis, PI's new Post Doc

As the PI did with Arcaro, he trained Girgis to support the BU CMS Upgrade electronics, under the guidance of Eric Hazen.

Contributing to HCAL hardware upgrades

Girgis comes to us after doing her PhD work at CERN from 2009 to 2014 in the groups of Centauro and Strange Object Research (CASTOR), Hadron Calorimeter (HCAL) and Forward Physics of CMS. As part of the CASTOR detector team, she participated in the early stages of detector assembly, testing of the detector materials, setup and data taking. She conducted analysis of detector response, energy resolution, energy linearity, and longitudinal and transversal development of showers for pions and electrons at various energies.

In HCAL under the guidance of Tkaczyk, she worked on hardware and software components of the Hadron Forward Calorimeter (HF), replacing old HF photomultiplier tubes (PMTs), installing them, and commissioning the HF calorimeter. She tested the new PMTs, cabling, data taking, and assembly of ROBOXs (the PMT containers). She conducted analyses of the PMT pedestal, gain, and relative response of LED and single photoelectron data. Hence she is ideally prepared to carry on the former duties of Phil Lawson and Arno Heister.

After being trained by the PI in electronics (as he did with Lawson and Arcaro before her), Girgis is testing the software and hardware of the AMC13s. She has developed an automated tool for testing AMC13 hardware using the Python language. This tool provides detailed testing of the hardware in both a supervised and unsupervised modes. It is used in the production and quality control pipeline.

Currently Girgis is writing an extensive suite of tests to exercise and verify correct operation of the AMC13 hardware, completely unattended. A specialized, domain specific language and the accompanying syntax parser appear to be needed to ease adoption of the tool and to make the software language independent. This implies creating a parser that understands how to evaluate handling errors and error messages, which she is working on.

Measuring forward jet cross-sections

In the Forward Physics Group, Girgis' research focused on a study of jet cross sections, again an excellent match with BU work. She has analyzed hadronic final states, studying the properties of quarks, including

the production rate of jets and the characterization of jet cross sections. She executed studies on HF reconstruction and performance, inclusive forward jets cross sections, and forward-central dijet cross-section measurements. Hence she will be immediately contributing to the analysis program outlined above.

4.e) Deploying Interns from the BU/CERN/DOE Program for 5-8 months at CERN each year.

The PI makes extensive use of undergraduate juniors at CERN, *e.g.* staffing the test beam, conducting radiation damage studies, evaluating SiPMs (with Y. Musienko), installing electronics (with Lawson and Arno Heister).

As a pro-bono effort and a part of his responsibilities during the two teaching semesters at BU, the PI directs the BU/CERN/DOE Internship Program. As cost sharing, the University provides matching funds to this DOE Task for undergraduate interns at CERN, in residence from mid-January through the end of August, working on CMS and other DOE projects under the direction of the PI and co-mentors at CERN. Each student works on the project 50% time from January through April, and 100% from May through the end of August. These students are selected from a group of 15 (1/2 from BU, 1/2 from other institutions) and monitored by the PI at CERN during the summer and by his on-site CERN co-director, Dr. Augusto Ceccucci (spokesman for NA62) during the winter and spring. These are the only undergraduate interns at CERN during the school term.

Internship projects span Energy, Intensity, Cosmic and Accelerator/Detector Frontiers. During the period of this grant, they includes, for example, prototyping CMS Phase 2 Upgrade GEM detectors, studying radiation damage of pixel devices for the ATLAS Upgrade, taking data in studies of superconducting magnet upgrades for the LHC, and contributing to the analysis of T2K data.

4.f) Service to the High Energy Physics Community and Outreach

In addition to his HEP research, the PI was active in the physics community during this 3-year grant. He served on the

Search Committee for the new Fermilab Director, and was a member of the
Board of Directors, Fermi Research Alliance (FRA, operator of Fermilab for the DOE), and
The FRA Visiting Scholars Selection Committee.

The PI engages in outreach activities and presented many talks in this period. In addition to being chosen by CMS and ATLAS to present their jet results at the

IXth Latin American Symposium on High Energy Physics.

He gave, for example layman presentations at

Saturday Morning Live, Goodwin House, Alexandria VA, *"Without those 'sticky' Higgs bosons, you'd be traveling at light speed"*

Maranatha Collegiate Academy, BWI, *"The Discovery of the Origin of Mass"*

Distinguished Lecture, Dartmouth College, *"Discovery of the Source of mass at the LHC?"*

5. Refereed and Published Papers all of which acknowledge support from DOE HEP.

The PI contributed significantly to 12 published papers (see below) during the 3-year period of this report. They fall into five categories, essentially all demanding knowledge of the performance of the hadron calorimeter of CMS. In total, they have been cited 735 times.

These are among the 403 that list him as an author in the *inSpire* database for the years 2013-16. In total they have been cited (excluding self-cites) 19k times, including 1 renown, 7 famous, 38 very well known, 72 well-known (50-99 cites) and 177 known papers (10-49 cites). This represents the CMS activity of some 2300 collaborators in CMS, and others in Super-K and Antares.

Vector boson fusion Higgs production, using, in part, tagging jets of the forward calorimeters, the reason why BU and the PI played a major role in getting the quartz fiber technology chosen for the forward calorimeter. In large measure, A. Heister and the PI initiated the VBF studies:

1. "Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes," CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) et al.). Apr 4, 2014. 35 pp. Published in Eur.Phys. J. C74 (2014) 8, 2980, CMS-HIG-13-030, CERN-PH-EP-2014-051, DOI: 10.1140/epjc/s10052-014-2980-6, e-Print: arXiv:1404.1344. (172 cites)

Missing Energy Signatures were a second motivation for adopting the forward calorimeter hermiticity advocated by the PI.

2. "Performance of the missing transverse energy reconstruction by the CMS experiment in sqrt(s) = 8 TeV pp data," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) et al.). Nov 3, 2014. CMS-JME-13-003, CERN-PH-EP-2014-246 e-Print: arXiv:1411.0511, JINST 10 (2015) P02006 (75 cites)

3. "Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at s√= 8 TeV," CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) et al.). Feb 19, 2014. 38 pp. Published in JHEP 1406 (2014) 055, CMS-SUS-13-012, CERN-PH-EP-2014-015, DOI: 10.1007/JHEP06(2014)055, e-Print: arXiv:1402.4770. (222 cites)

Searches for Long-Lived Particles, pursued primarily by A. Heister, the PI's former research professor colleague and current collaborator from Aachen.

4. "Search for long-lived particles that decay into final states containing two electrons or two muons in proton-proton collisions at sqrt(s) = 8 TeV," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) et al.). Nov 25, 2014. CMS-EXO-12-037, CERN-PH-EP-2014-263 e-Print: arXiv:1411.697711, Phys. Rev. D 91 (2015) 052012. (38 cites)

5. "Search for long-lived particles decaying to photons and missing energy in proton-proton collisions at s√=7 TeV" CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) et al.). Dec 2012. 29 pp. Published in Phys.Lett. B722 (2013) 273-294 CMS-EXO-11-035, CERN-PH-EP-2012-342 DOI: 10.1016/j.phys let b.2013.04.027 e-Print: arXiv:1212.1838 [hep-ex]. (34 cites)

Studies of Jets, especially with Z's, for which the forward calorimeter was designed and prototyped by the PI as spokeman of the effort at the time. Contributions came from P. Lawson, the PI's former graduate student, as part of his PhD thesis.

6. "Measurement of the inclusive jet cross section in pp collisions at s√=2.76TeV,"
CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Dec 19, 2015. 30 pp.
Published in Eur.Phys.J. C76 (2016) no.5, 265, CMS-SMP-14-017, CERN-PH-EP-2015-299,
DOI: 10.1140/epjc/s10052-016-4083-z, e-Print: arXiv:1512.06212 (4 cites)

7. "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Jul 13, 2016. 92 pp. (13 cites)

8. "Measurements of jet multiplicity and differential production cross sections of Z+jets events in proton-proton collisions at sqrt(s)=7 TeV," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) et al.). Aug 13, 2014. 39 pp. CMS-SMP-12-017, CERN-PH-EP-2014-205, e-Print: arXiv:1408.3104, Phys. Rev. D 91 (2015) 5, 052008. (29 cites)

9. "Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross-section in pp collisions at s√= 7 TeV," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) et al.). Oct 24, 2014. 61 pp. CMS-SMP-12-028, CERN-PH-EP-2014-238, e-Print: arXiv:1410.6765, Eur. Phys. J. C 75 (2015) 288. This work was the continuation of Lawson's PhD thesis initiative. (45 cites)

10. "Study of hadronic event-shape variables in multijet final states in pp collisions at sqrt(s) = 7 TeV," CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) et al.). Jul 10, 2014. 34 pp. Published in JHEP 1410 (2014) 87, CMS-SMP-12-022, CERN-PH-EP-2014-146, DOI: 10.1007/JHEP10(2014)087, e-Print: arXiv:1407.2856, Eur. Phys. J. C 75 (2015) 288. This work was started as a part of the PhD thesis of P. Lawson. (45 cites)

11. "Event shapes and azimuthal correlations in Z + jets events in pp collisions at √s = 7 TeV," S. Chatrchyan et al., The CMS Collaboration, arXiv:1301.1646 v2 [hep-ex] 8 May 2013, also Phys. Lett. B 722 (2013) 238, 24 May 2013. (53 cites)

Drell-Yan production.

12. "Forward–backward asymmetry of Drell–Yan lepton pairs in pp collisions at s=√8 TeV"
CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.*). Jan 18, 2016. 36 pp.
Published in Eur.Phys.J. C76 (2016) no.6, 325, CMS-SMP-14-004, CERN-PH-EP-2015-295,
DOI: 10.1140/epjc/s10052-016-4156-z, e-Print: arXiv:1601.04768 (5 cites)

6. People who worked on this research activity, most of whom received partial support, directly or indirectly, from this award, as well as from Boston University:

1) Prof. Sulak's (PI) Research Group:
Graduate Students:
Dr. Phil Lawson, BU Upgrade electronics responsibilities got his PhD in 2013.
Dan Arcaro, Graduate student, Lawson's replacement, poised to get his PhD in 2017.
Arcaro has worked on CMS HCAL hardware and analysis for the last three years, and with Eric Hazen on CMS electronics for the last two. He is currently focusing on software for the the AMC13 upgrade of HCAL as a full-time resident at CERN. He was minimally supported by this DOE grant for the summers of 2014 and 2015, and for 3 months of 2016; the BU Physics Department generously supported him otherwise.
Colin Jacob, Graduate student, being trained on CMS electronics, potential Arcaro replacement (supported by the BU Physics Department)

Research Prof. / Post-Docs
Prof. Arno Heister, now at the University of Aachen as of 2014, continues to consult with the PI on CMS HCAL legacy hardware and software.
Dr. Semiray Girgis, who assumed Heister's responsibilities. She is currently awaiting funding.

Primary external collaborator
Dr. Slawek Tkaczyk, Fermilab Senior Scientist, in full-time residence at CERN. Co-mentor for Arcaro when the PI is not at CERN.

The PI's Undergraduate Interns, in residence at CERN January to September
(of a total of 15 in the BU/CERN/DOE Program)
2013: William Nash, Dave Corbino, and Adi Foord
2014: Logan Kageorge, and Ivan Lavrentyev
2015: Guy Rosin, Inna Gertsenshteyn, and Logan Kageorge

2) BU Electronics Engineers, supported primarily through CMS project funds and by Boston University:
Eric Hazen, Director, BU Electronics Design Facility
Shouxiang Wu

3) BU colleagues working synergistically on CMS with different DOE Tasks during the period of this grant:
Prof. Tulika Bose
Dr. Aram Avetisyan (Postdoctoral Fellow)
Dylan Rankin (graduate student)
Clint Richardson (graduate student)

Prof. Jim Rohlf
David Zou (3rd year grad student, currently working at CERN, training Arcaro)

4) Joint Professor and collaborator at the University of San Francisco de Quito of Ecuador:
Prof. Edgar F. Carrera
Daniel Ibarra (graduate student, worked with the PI at CERN during the summer of 2014)

5) Dr. Dragoslav Lazic, Research Physicist, funded by CMS project funds.

7. Unexpended funds
Some ~$200 are anticipated to be returned to the DOE at the end of the current budget period.

8. Supplemental Budget Request for FY2017 and beyond: high priority supplemental work that does not fit in the budget of the new grant for FY17-19.

We request supplemental funds in FY2017 that are < 25% of those awarded, with no change in the research scope.

We propose reinstating the funding of 15 undergraduates in the BU/CERN DOE Internship Program from January through August of each year, at an incremental direct cost of $36k. Funding for this program, which has been a part of the DOE grant to this PI since 2009, was no longer available as of May 2016. This funding supplement should be viewed in the context of the PI devoting full time for 4 months in

residence at CERN, involved in CMS maintenance, upgrade and/or data analysis each summer since 2003 (typically May 9 to September 9). The current compensation for this is only 1 month of capped summer salary to support 4 months of work. This request for continued funding was presented to and reviewed by Dr. Abid Patwa at CERN on July 29, 2016.

We also request minimal salary funding for Girgis (or a replacement graduate student for Arcaro) to continue supporting the commissioning and development of software for the AMC13 for the CMS Hadronic Calorimeter Upgrade. Girgis has taken over the electronics responsibilities of Phil Lawson (who got his PhD in 2013), Arno Heister, and, at BU, those of Dan Arcaro (who is expected to get his PhD at the end of 2017). Arcaro is working with David Zou, who will move back to BU from CERN at the end of the summer of 2016, leaving BU with no funded physical presence in the Electronics Design Facility, subsidized 50% by the university, for projects who have a physicist assigned there. We need Girgis there to fulfill our CMS hardware upgrade responsibilities.