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HIGH ENERGY ACCELERATOR AND COLLIDING BEAM USER GROUP

at the

UNIVERSITY of MARYLAND

UNIVERSITY OF MARYLAND
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Abstract

HIGH ENERGY ACCELERATOR AND COLLIDING BEAM USER GROUP at the UNIVERSITY of MARYLAND

Principal Investigator: Nicholas Hadley
Applicant: University of Maryland, College Park

We have finished the third year of a three year grant cycle with the U.S. Department of Energy for which we were given a five month extension (U.S. D.O.E. Grant No. DEFG02-96ER41015). This document is the final report for this grant and covers the period from November 1, 2010 to April 30, 2013.

The Maryland experimental HEP group consists of six teaching faculty (A. Baden, S. Eno, N. Hadley, A. Jawahery, D. Roberts and A. Skuja) and one research scientist (R. Kellogg). The Maryland experimental HEP group has been involved in two major experiments – BaBar and CMS. We have started design and R& D work towards a Super B experiment and have recently joined the LHCb experiment. Maryland Physicists have played leadership roles in detector development, installation, maintenance, and management as well as physics analysis in all of these experiments.

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Chapter 1

Overview

1.1 The Maryland High Energy Physics Grant

We have finished the third year of a three year grant cycle with the U.S. Department of Energy for which we were given a five month extension (U.S. D.O.E. Grant No. DEFG02-96ER41015). This document is the final report for this grant and covers the period from November 1, 2010 to April 30, 2013. The Maryland program is administered as a single task with Professor Nicholas Hadley as Principal Investigator.

The Maryland experimental HEP group is focused on two major research areas. We are members of the CMS experiment at the LHC at CERN working on the physics of the Energy Frontier. We are also analyzing the data from the Babar experiment at SLAC while doing design work and R&D towards a Super B experiment as part of the Intensity Frontier. We have recently joined the LHCb experiment at CERN. We concluded our activities on the DØ experiment at Fermilab in 2009.

1.2 Faculty

The University of Maryland High Energy Physics Group consists of seven active faculty members: A. Baden (Drew) (Professor and Department Chair), S. Eno (Professor) N. Hadley (Professor), A. Jawahery (Hassan) (Professor), R. Kellogg (Senior Research Scientist), D. Roberts (Associate Professor), and A. Skuja (Professor)

Dr. Alberto Belloni joined the group as an assistant professor in January 2013. He will work on the CMS experiment. Dr. Belloni will initially be supported by his start-up funds and his work will not be discussed further in this report as he was not supported on grant funds during this period. Dr. Belloni received his PhD from MIT working on the CDF experiment and was a postdoc on the ATLAS experiment at Harvard.

1.2.1 Summary of Faculty Program

Prof. Drew **Baden** worked on CMS during this grant period. On CMS, Prof. Baden is a US Level 3 manager with responsibility for the CMS Hadron calorimeter digital electronics. Maryland designed and built the Hadron Calorimeter Trigger (HTR) cards for this system. Prof. Baden is also US CMS coordinator of the calorimeter upgrade for the Super LHC and works along with a graduate student and postdocs on searches for leptoquarks and other new phenomena.

Prof. Sarah **Eno** has been co-leader of the CMS Jets and Missing E_T group, the SUSY-BSM group, the Exotica group. She is also a member of the CMS publications committee. She works along with graduate students and postdocs on searches for leptoquarks and stopped gluinos as well as other searches for exotic particles and Monte Carlo simulations of upgrades of the calorimeter for SLHC.

Prof. Nick **Hadley** is the Chair of the US CMS Collaboration Board. This is the highest elected position in US CMS. He is also the Country Coordinator for the US and represents US interests in the CMS Management Board and on the CMS committees that select the appointed members of CMS management. He and a student and postdoc worked on the measurement of the top quark cross section. He has recently shifted his activities to searches for new physics.

Prof. Hassan **Jawahery** was the spokesperson of the BaBar experiment (September 2006 - September 2008). Under his leadership, the Maryland group has been at the forefront of the measurements of charmless B decays, leading to information on CKM angles α and γ. Currently, he and his students and postdoc are working on the analysis of the BaBar data in several areas. He is one of the main proponents of the proposed Super B experiment at Frascati. He has recently joined the LHCb experiment at CERN and will participate in its operation and physics exploitation as well the development of its upgrade program

Prof. Doug **Roberts** is currently working on the BaBar data analysis and Super B R& D. He has led the BaBar effort of the measurements of double charm decays ($B \to D^{(*)}D^{(*)}$), including CP violation studies in these modes. He is active in the Super B particle identification subgroup and in Super B physics studies. He has recently joined the LHCb experiment at CERN and will participate in its operation and physics exploitation as well the development of its upgrade program

Prof. Andris **Skuja** is working on the CMS experiment at the LHC and the Hadron Calorimeter System (HCAL) in particular. Prof. Skuja became the (International) CMS HCAL Project Manager in mid 2006 and retained that position until mid 2009. His tenure included the crucial installation and commissioning phase of the HCAL calorimeter. He was Deputy HCAL Project Manager from 2009-2011 and is now a member of the HCAL Advisory and Executive boards. Currently, he works on long lived quasi stable particle searches as well as helping coordinate the photodetector replacement with SiPMs of the outer hadron calorimeter for 2013–2015.

Research Scientist Richard **Kellogg** is working on the CMS experiment. He has focused his efforts on the installation, commissioning and operations of the CMS Hadron Calorimeter. Dr. Kellogg was responsible for the installation and commissioning of the HCAL Trigger/DAQ electronics system at CERN. Dr. Kellogg is the operations expert for all of the HCAL electronics at CERN, including the front-end electronics designed and manufactured by FNAL.

1.3 Postdoctoral Physicists and Graduate Research Assistants

The following post-doctoral physicists have been supported on the grant during the past three years:
BaBar: Ricardo Cenci and Ellie Twedt
CMS: Jeff Temple, Paolo Rumerio, Francesco Santanastasio, Ted Kolberg, and Matthieu Marioneau. Rumerio became an assistant professor of physics at the University of Alabama in January 2012, and Santanastasio became a CERN Fellow in September 2011.

During 2009-2012, the experimental program supported 13 graduate research assistants: Ken Rossato, Ellie Twedt, Malina Kirn, Dinko Ferencek, Brian Calvert, Alison Peterman, Kevin Pedro, Chris Anelli, Young Shin, Brian Hamilton, Edward Behn, Jason Andrews, and Jack Wimberley. Rossato, Twedt, Ferencek, and Kirn obtained their PhDs in 2011 on the data from the 2010 LHC run. We have had no difficulty in attracting good graduate students to experimental High Energy Physics, and would have more if funding permitted. We also supported nine part-time undergraduate students at various times during the last three years: Walter Muench, Hannalore Gerling-Dunsmore, Noah Mandell, Roland Jeannier, Michael Kossin, Ethan Cowan, Jonathan Wonders, Oliver Pierson, and Stephen Guth.

1.4 Professional and Administrative Personnel

We supported a part-time electronics engineer, Rob Bard. Bard is crucial for the continued maintenance of electronics for our current and proposed experiments. CMS electronics has also been designed and commissioned by Tullio Grassi (an electronics engineer) fully supported by the CMS project funds and CMS M&O funds.

We were assisted by two administrative staff members (both part-time), partially compensated out of the present DOE/HEP grant. They are B. Dunn (Administrative Assistant - part time) and S. Megonigal (Administrative Assistant - part time). Combined our administrative staff members are equivalent to less than one FTE. The administrative staff was also partially funded by the University. Our accounting clerk, Ms. Xiao-ning Zhao, was totally funded by the Department of Physics.

We provided a small amount of partial support for Dr. Suresh Tonwar, who is visiting Maryland from the Tata Institue in India, and working on CMS. We also provided a small amount of support to Dr. Marguerite Tonjes, who helps administer our CMS Tier 3 cluster. Dr. Tonjes is a member of the Maryland Chemistry department working on CMS Heavy Ion Physics, and is primarily funded by DOE Nuclear Physics.

Chapter 2

Study of Heavy Flavor Physics and CP Violation - Intensity Frontier

2.1 Overview

The heavy flavor physics group at Maryland has been an institutional member of the *BaBar* experiment from the outset, with major involvements in most aspects of the experiment, including the design, construction and commissioning of the detector, development of its reconstruction software, analysis of the data, and management of the experiment. In the following sections we will summarize our contributions to the experiment and a proposed program for completing our data analysis effort.

A major focus of our research activities in the current funding cycle has been on the development of a new facility for precision studies of heavy flavor and CP violation. Jawahery presented the physics case for a Super Flavor experiment- "Physics Opportunities at a B Factory in the LHC Era" to the High Energy Physics Advisory Panel (HEPAP) in May 2009. Our group has been an active member of the INFN SuperB collaboration, has had a leading role in the US program on the experiment, and has been deeply engaged in the design of the detector. Although the SuperB project received initial approval and funding from the Italian government in December 2010, the approval and funding for the development and construction of the project has been delayed and is now contingent upon further reviews by the new Italian government in Fall 2012. The earliest time for the start of the construction of the project is now in 2014 with completion in 2020. Therefore, we have decided to pursue our long-standing interest in heavy flavor physics by participating in the LHCb experiment and the development of its upgrade program. Our proposed program for participation in the experiment has been reviewed and positively received by the membership committee of the collaboration. On September 5, 2012, the LHCb collaboration board voted to admit the Maryland group as a full member of the LHCb collaboration. The LHCb program will provide an exciting opportunity for precise studies of flavor physics which will contribute to the search for physics beyond the Standard Model.

2.1.1 Personnel

The members of the Maryland Heavy Flavor physics group at the end of the funding period were:

- Hassan Jawahery (Faculty)
- Douglas Roberts (Faculty)
- Riccardo Cenci (Research associate, 2009-present)
- Elizabeth Twedt (Research associate 2011-present)
- Brian Hamilton (Graduate research Assistant, 2009-present)
- Jason Andrews (Graduate research Assistant, 2012-present)
- Jack Wimberley (Graduate research Assistant, 2012-present)

Our past postdoctoral research associates on *BaBar* were:

- Carlo Dallapiccola (now associate professor at Univ. of Massachusetts)
- Jochen Schiek (now Professor at Ludwig-Maximilians-Universitat, Munchen)
- Jim Olsen (now professor at Princeton U.)
- Wouter Hulsbergen (now senior research staff at NIKHEF)
- Chunhui Chen (now assistant professor at Iowa State Univ.)
- Gabriele Simi (now assistant professor at Univ. of Padova)

Our past graduate students on *BaBar* were: Amir Farbin (Now assistant professor at Univ of Texas, Arlington), Bram Lillard (Industry), Chung Khim Lae (postdoc at John Hopkins/Syracuse), Dmyrto Kovalskyi (postdoc at UC, Santa Barbara/CMS), Jake Anderson (now postdoc at Fermi lab/CMS), and Joe Tuggle (now postdoc at Univ. of Chicago/ATLAS), Edward Behn (Graduated with a Master degree, 2009-2012).

We have been assisted by our electronic engineer Robert Bard. We have also typically supported one or two undergraduate researchers in the program.

2.2 The BaBar program

In the current funding cycle FY2010-2013, which roughly coincided with the "intense analysis period" of the post data taking phase of the experiment, we initially completed and published several analyses involving measurements of the CKM parameters, and CP violating (CPV) asymmetries in rare B decays. The focus of our analysis effort was then shifted to new topics: measurements of direct CPV in charm decays, searches for FCNC decays of charmed mesons, measurement of the B_s^0 semileptonic branching ratio using the data collected above the $\Upsilon(4S)$ resonance, measurement of charm production in decays of Υ resonances, and measurements of anti-deuteron production in quark and gluon fragmentation. The latter is motivated by astrophysical interests in anti-deuteron production as a probe of dark matter annihilations. Most of these analyses have now been published. We plan to complete and publish the remaining on-going analyses listed below in the coming year, bringing to conclusion our work on the physics analysis of the *BaBar* data:

- A broad study of direct CP violation in two-body decays of charmed mesons. This program has already produced the most precise measurement of CPV asymmetry in the charm system ($A_{CP}(D^+ \rightarrow K_s^0 \pi^+)$) (published), showing evidence for CP violation induced by indirect CPV in the K^0 system.
- Measurements of the production rates of anti-deuteron in quark and gluon fragmentation using the *BaBar* data at the Υ resonances as well as the continuum e^+e^- annihilation near the 4S resonance.
- Search for Flavor Changing Neutral Current decays and Lepton Flavor Violating decays of the D^0 meson. This work is complete and will be published in the coming months.

The main goals of the *BaBar* experiment were: (1) to establish the presence or absence of CP violation in B decays, (2) to test the validity of the the Standard Model mechanism for CP breaking by precise measurements of the sides and the angles of the CKM unitarity triangle, and (3) search for physics beyond the SM via rare B decays. The actual physics output and the impact of the experiment, however, far exceeded the scope of the original goals.

The construction and commissioning of the PEP-II machine was completed in 1998 and the *BaBar* detector operated in colliding beam mode from April 1999 until April 2008, culminating in an integrated luminosity of 528 fb^{-1}. While most of the data is collected at the $\Upsilon(4S)$ resonance, the final 3 months of the run were devoted to running on the $\Upsilon(3S)$ and $\Upsilon(2S)$ resonances and a scan of the energy region above the $\Upsilon(4S)$.

We have had a leading role in the program, with significant responsibilities in the management of the experiment at various levels. Jawahery served as *BaBar* spokesperson (2006-2008), physics analysis coordinator (2001-2002), co-chair of the working group on the design of new computing model (2002), convener of the B & charm hadronic group (2000-2001), and first convener of the charmless B decays working group (2000). Roberts served as the coordinator of the SVT alignment effort, and the SVT co-system manager (2003-2008). Our postdocs served as conveners of physics working groups: Jim Olsen (charmless decays), Wouter Hulsbergen (Radiative B decays, and tracking), Chunhui Chen (final sin2beta measurement, and on-site SVT operation manager), Gabriele Simi (charmless 2-body decays, and tracking).

The Maryland group had significant involvement in the design, construction, commissioning and the operation of the *BaBar* detector. These included: Initial R&D on choices of particle identification system for *BaBar* design and deployment of the environmental monitoring system for the drift chamber (DCH), and continuing support of the DCH operation during the data taking phase, commissioning of the Silicon Vertex Tracker (SVT), and support and leadership of its operation during the data taking phase, commissioning and operation of the *BaBar* detector control and monitoring system in the initial 2-years of its operation.

We were major contributors to the development and maintenance of the tracking software throughout the life of the experiment. These include, the development of the SVT internal alignment method and its implementation, and a software package for reconstruction of secondary vertices and kinematic fitting, which has been in wide use in the collaboration. Our research associates (Hulsbergen and Simi) served as conveners of the *BaBar* tracking group.

We have also had a deep involvement in the physics analysis of *BaBar* data as described in the following section.

2.2.1 Physics Analysis of the *BaBar* data: Recent work completed and on-going analyses

During the data taking phase of the experiment, our physics analysis effort was centered on the measurements of CP violation in B decays and searches for new physics effects through loop dominated processes. A list of the publications resulting from our analyses work is presented in the final section of this report, "Previous Maryland Work on *BaBar* Physics Analysis". The group has been at the forefront of the measurements of 2-body charmless B decays, a primary contributor to the determination of the CKM angles α and the observation of direct CPV in B decays, the measurements of the double charm decays ($B \to D^{(*)}D^{(*)}$), including CP violation in these modes. We pioneered a novel analysis technique for measuring time-dependent CPV asymmetries in decay modes such as $B \to K_s^0\pi^0$ and $B \to K^{*0}\gamma$(with $K^0 \to K_s^0\pi^0$), which contain no charged particles at the B decay vertex. Access to CP asymmetries in these modes significantly enhanced the capability of the experiment in the search for physics beyond the Standard Model. Our final analysis results in these areas with the full *BaBar* data set were completed and published in the 1st year of the current funding cycle:

- 'Measurement of time dependent CP asymmetry parameters in B^0 meson decays to ωK_s^0, $\eta' K^0$, and $K_s^0\pi^0$," Phys. Rev. D **79**, 052003 (2009) [with Colorado and Milan groups]
- "Measurements of TIme-Dependent CP Asymmetries in $B^0 \to D^{(*)+}D^{(*)-}$ Decays", Phys Rev. D **79**, 032002 (2009)
- "Measurement of Time-Dependent CP Asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ Decays.", Phys. Rev. D 79, 072009(2009) (with U Irvine, Frascati, Queen Mary, Rome)

We have since focused our analysis effort on the following topics:

- **CP violation in charm decays**
  CP violation in the charm sector is currently the subject of intense theoretical and experimental attention. The Standard Model predicts extremely small CP violation in the charm sector (both GIM and CKM suppressed), thus the observation of significant CPV in charm decays would be indicative of the presence of new physics effects. The *BaBar* data, containing roughly 10^9 charm decays, allows for precise ($\approx$ per mill) measurements of CPV asymmetries in certain channels. The main challenge is to match the per mill statistical sensitivity with similar, or better, systematic accuracies. Amongst the major sources of systematic uncertainties are the charge asymmetries in track reconstruction and in background contributions . We devised a novel method for estimating and correcting for these effects, allowing for a measurement of the CPV asymmetry, $A_{CP}(D^+ \to K_s^0\pi^+) = -0.44 \pm 0.13(stat) \pm 0.1\%(syst)$, at the time the most precise CPV asymmetry measurement in charm decays (Phys.Rev.D(RC) **83**, 071103 (2011). The measured non-zero asymmetry (at $\approx 3\sigma$ significance) in this mode is

consistent with the expected value due to indirect CPV in K^0 system (ϵ_K). Thus far, we find no evidence for direct CP violation in this Cabibbo-allowed decay channel. We have extended the analysis to several channels with similar topologies, $D^+ \to K_s^0 K^+$, $D_s^+ \to K_s^0(\pi^+, K^+)$ and $D^0 \to K_s^0 P^0$ where $P^0 = (\pi^0, \eta, \eta^{'})$, and expect to complete and publish the results in the coming months.

LHCb and CDF have recently reported evidence for direct CPV in singly Cabibbo-suppressed charm decays, $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$. They report measurements of the asymmetry difference, $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^) = -0.82 \pm 0.21 \pm 0.11\%$ (LHCb), which is significantly larger than the nominal predictions based on the SM. This has stimulated significant experimental and theoretical interest in examining the SM prediction, as well as possible new physics interpretation of the CPV asymmetries in charm decays (e.g. arXiv:1111.5000, 1203.6659).

- **Measurement of the inclusive semileptonic branching ratio of the B_s^0 meson**

In the final week of data taking with *BaBar* we performed a scan of the energy region above the $\Upsilon(4S)$ resonance, from CM energy of 10.54 to 11.20 GeV in steps of about 5 MeV. The primary motivation for this run was to search for exotic bottomonium states, analogs of the so-called XYZ-states observed above the charm threshold, such as the Y(4260) or Y(4350) states. A study of the data does not show any evidence for new structures in this region. The initial analysis of this data also yielded a measurement of $R_b(s) = \sigma_b(s)/\sigma^0_{\mu\mu}(s)$, and new measurements of the parameters of the $\Upsilon(5S)$ and $\Upsilon(6S)$ resonances. The $\Upsilon(5S)$ is above the threshold for $(e^+e^- \to B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)})$, allowing the study of production and decay of the B_s^0 meson.

We have performed an analysis of this data set to determine the cross section for B_s production as a function of CM energy and the semileptonic branching ratio of the B_s^0 meson. The analysis exploits the inclusive production of ϕ meson, and ϕ meson production associated with a high momentum lepton (electron or muon) to perform a simultaneous determination of the B_s^0 semileptonic branching ratio and the B_s^0 production fraction relative to other B mesons. We determine the B_s^0 semileptonic branching fraction to be $9.5^{+2.6+1.1}_{-2.1-1.9}\%$, published in Phys.Rev.D(RC) **85** 011101 (2012), representing the first published measurement of the B_s^0 semileptonic branching ratio.

- **Measurement of charm production in decays of bottomonium resonances**

A class of transitions in the Υ resonances, for which scarce experimental information exists, is the decay of $b\bar{b}$ resonances to open charm hadrons. For two of the χ_b states the process has been observed by CLEO and the branching fractions have been measured to be about 10%, in agreement with predictions from non relativistic QCD. For the Υ system, the decay through a virtual photon is allowed and is estimated to be about 1.5% for the $\Upsilon(1S)$ decays. Non relativistic QCD calculations predict additional contributions due to the $c\bar{c}gg$ transition and due to the color octet mechanism for which no experimental confirmation exists. A measurement of the inclusive rate for $\Upsilon(1S) \to (charmed - hadron)X$ would provide important information to test these predictions. We performed this analysis with the *BaBar* data taken at the Υ resonances, obtaining a measurement of the branching ratio

$B(\Upsilon(1S) \to D^{*+}X) = (2.59 \pm 0.13 \pm 0.15)\%$, and the D^{*+} momentum spectrum in the rest frame of the $\Upsilon(1S)$ resonance. We find evidence for an excess of D^{*+} production over the expected rate from virtual photon annihilation process $\Upsilon(1S) \to \gamma^* \to c\bar{c} \to D^{*+}X$. Our measurement shows that the excess D^{*+} production is primarily in the region of scaled momentum $X_p < 0.75$, and disfavors octet contributions. The results are published in Phys.Rev.D(RC) **81** 011102 (2010).

- **Measurements of anti-deuterium production in gluon and quark fragmentations** The cosmic anti-deuteron flux has been proposed as a potential probe of dark matter annihilation (arXiv:1006.0983, 1201.3849, 1012.06273), owing to its extremely low expected flux from astrophysical sources. Limits on the astrophysical flux of cosmic ray anti-deuterons is anticipated to improve by a factor of ≈ 1000 at the upcoming experiments AMS-02 and GAPS, from $10^{-4}[\mathrm{m}^2\mathrm{ssr}GeV^{-1}]$ to 10^{-7}. Given that the expected flux from astrophysical sources is nearly two orders of magnitude lower, the detection of an anomalous anti-deuteron flux would be evidence for a new primary source of anti-deuterons. One possible source of anti-deuterons is dark matter annihilating to colored particles (quarks and gluons), which in turn fragment into baryons and mesons. However, the poor knowledge of the anti-deuteron production in the fragmentation processes leads to significant uncertainties in the predictions of the anti-deuteron flux. The *BaBar* data, with its rich mix of Υ decays and continuum $e^+e^- \to q\bar{q}$, allows for measurements of anti-deuteron production in gluon and quark fragmentations in the 10 GeV CM energy region.

  Previously, antideuteron production in electron-positron collisions was studied by ALEPH at the Z pole and by CLEO in the region of the Υ resonances. Using the *BaBar* dataset, we expect to significantly improve on CLEO's Υ results and observe or improve limits on production in continuum and $\Upsilon(4S)$. Work is currently in progress to perform a measurement of the anti-deuteron rate over a wide momentum range. We expect to complete and publish these results in the next few months.

2.3 Future program on precision flavor physics and CP Violation

The past decade saw major advances in flavor physics. These include the discovery of CP violation in B decays at the B factories, which led to the confirmation of the CKM mechanism as the primary source of the observed CP-violating phenomena, and the observations of the B_s^0 mixing at Tevatron and the D^0 mixing at the B factories. In addition, a broad set of loop-level FCNC processes have now been measured at the B factories and Tevatron. Although nearly all flavor physics observables are consistent with the CKM picture and the Standard Model predictions, higher precision measurements of loop dominated flavor processes are have the potential to reveal the presence of new physics through discrepancies with the SM and help in pinning down its flavor structure. This indirect approach has had an extremely successful track record in predicting new effects (e.g. the charm quark and its mass from K^0 mixing and rare K decays, the top quark mass from B^0 mixing and EW measurements, and most recently the mass of the Higgs boson) later confirmed by direct observations. The goal of the next phase of heavy flavor physics experiments is order-of-magnitude improvements in the precision of key flavor physics observables, including CKM parameters, CPV asymmetries, kinematic parameters and branching ratios in rare loop-dominated B and D decays and the search for charged lepton flavor violating decays. With the expected improvements of both the measurements and the related theoretical calculations, flavor physics is poised to remain at the forefront of the search for new physics, and if found, the discovery of its flavor structure.

On the experimental front, the prospects for precision measurements in the heavy flavor sector rest on three facilities: the LHCb experiment and its upgrade plans at the CERN LHC collider, and two proposed e^+e^- "Super B factory" colliders operating in the Υ energy region. The Belle-II experiment in Japan and the INFN SuperB experiment in Italy aim at a peak luminosity of around $10^{36} cm^{-2} s^{-1}$, using the novel "nano-beam" scheme proposed and developed by P. Raimondi et al, allowing for a data set of $\approx 50 - 75 fb^{-1}$ in 5 years of running, about two orders of magnitude increase over the BaBar and Belle data sets.

The Maryland group has been a member of the INFN Super B collaboration, working on the development of the particle identification system and coordination of the US program. The details of our contributions are presented below. As discussed previously, given the time scale of the development of the INFN SuperB factory and funding uncertainties, we have decided to pursue our flavor physics research program by joining the LHCb experiment.

We have developed a sophisticated photodetector testing facility at Maryland, described below, which can be employed in testing and characterizing MaPMT's for the RICH2 detector in LHCb.

2.3.1 The SuperB program

Our group has been an active member of the INFN SuperB collaboration with major roles in the design of the detector, and coordination of the US program on the experiment.

A list of the main areas of our contributions to the program is:

- Coordination of the US Super B program. Jawahery served as the PI for the US SuperB community since 2011.
- Design and Development of the Particle Identification system (Roberts, Jawahery and Twedt).
- Development of simulation tools for studying the SuperB detector performance, and the evaluation of beam induced backgrounds in the Super B detector (Roberts, Simi, Cenci)

The Super B detector concept is largely based on the *BaBar* detector concept, and the reuse of its key components. Its components are: a tracking system consisting of a silicon vertex tracker and a drift chamber, a focusing DIRC for the barrel particle identifications system, the refurbished *BaBar* CsI calorimeter for barrel calorimetery, all within a 1.5 T field superconducting solenoid (reused *BaBar* solenoid), and the Instrumented Flux Return of the magnet as the muon and K_L identification system. A forward PID system and electromagnetic calorimetery using radiation hard and fast crystals is also envisioned

Particle Identification for the Super B detector

We have been engaged in the design and optimization of the focusing DIRC, in collaboration with the SLAC group B and other US, Italian and French institutions. This includes R&D on pixelated photodetector technologies, preparation of a full size prototype, and simulation studies on the design and performance of the detector.

A prototype of the FDIRC has been prepared and will be tested in cosmic rays. This prototype utilizes a spare set of *BaBar* DIRC quartz bars and manufactured quartz focusing elements as will be used in SuperB. The prototype will be placed in the SLAC Cosmic Ray Telescope in the Fall of 2012. While the readout will not be fully instrumented and will not use the final electronics, the optics of the system will be the same as in SuperB. This will allow us to verify the detector design. Maryland has had major responsibilities the design and preparation of the prototype, including pre-amplifiers for the photodetector, and the development of the reconstruction and calibration software.

Super B Simulation Effort

We have worked on the development of a fast simulation code for the SuperB detector, in collaboration with colleagues from LBL, Caltech, U. Cincinnati and LNF in Rome. The Maryland contribution is primarily to the simulation of the tracking effects. The SuperB fast simulation work has been published in J.Phys.Conf.Ser. **331** (2011) 032038.

Dr. Cenci has been a member of the Machine Detector Interface group and has performed extensive studies of the expected particle rates in different regions of the detector, using a detailed MonteCarlo model of the machine final focus, detector and surroundings areas.

2.4 Photon Detector Laboratory

We have developed an advanced photon detector laboratory, enabling us to test and characterize a variety of photon detectors used in High Energy Physics experiments. The laboratory, devised and developed by Dr. Roberts with help from our electronics engineer Rob Bard and research associate Dr. Twedt, has an extensive setup for testing and measuring Multi-Anode Photomultiplier Tubes (MaPMT). This type of detector is being considered as the baseline photon detector for both the SuperB Focusing DIRC Particle ID system and the LHCb RICH system upgrade. Both experiments have similar requirements for MaPMT performance, requiring single photon detection with precise position and time information.

We have tested the Hamamatsu H8500, H9500 and R11265 MaPMTs, all of which are potential candidate tubes for these experiments. The H8500 (baseline for SuperB) is a 64-channel (8×8) square tube with an active area of $49 \times 49\text{mm}^2$ and a pixel size of approximately $6 \times 6\text{mm}^2$. The H9500 is a 256-channel (16×16) square tube with the same physical dimensions of the H8500 but with a pixel size or approximately $3 \times 3\text{mm}^2$. The R11265 is a smaller square tube ($23 \times 23\text{mm}^2$) with 64-channels (8×8) and a pixel size of approximately $2.9 \times 2.9\text{mm}^2$. All three tubes have similar gain and timing characteristics, and the square tubes allow for high packing density and therefore greater photon collection efficiency.

The MaPMT testing setup consists of a dark box housing the MaPMT under test and a conventional single channel PMT used as a reference. An x, y stepping motor system allows to scan a light source over the face of the MaPMT. The primary light source is a PiLAS 410nm picosecond pulsed laser diode, coupled to the dark box via single-mode optical fibers. The light intensity can be adjusted using a system of neutral density filters. In the dark box, the light is sent through a lens system that can produce a $< 50\mu$m (4σ) spot size on the face of the tube. The signals from the tubes are recorded using 3 CAEN V1742 waveform digitizer module. The V1742 is a 32 channel, 12 bit, 5 GigaSamples/s digitizer. This allows us to store complete waveforms for off-line analysis and the sample rate is sufficiently high to make precise transit time spread measurements for these MaPMTS. The entire system is controlled, coordinated and automated using LabVIEW. The automation of the system would allow us to easily convert what is currently an R&D laboratory into a full scale Q&A facility capable of testing and calibrating a large number of tubes. The SuperB FDIRC would require approximately 600 H8500 MaPMTs, while the LHCb RICH upgrade would require approximately 3700 R11265 MaPMTs.

With this system we were able to study the uniformity of the MaPMT's response across its face, cross-talk between pixels, position resolution, gain and timing characteristics. Our ability to produce a very small laser spot size on the face of the tube has allowed us to study effects due to the internal structure of the tubes. Since the primary use case for the MaPMTs will be as photon detectors for Čerenkovring imaging devices, we have been focused on studies of the tubes to single photon light levels.

Chapter 3

Hadron Collider Physics with the CMS Detector at the LHC - Energy Frontier

Professors A. Baden, S. Eno, N. Hadley and A. Skuja are members of the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN. They are joined by Senior Research Scientist R. Kellogg as well as their junior colleagues from the University of Maryland. The CMS collaboration is analyzing proton-proton collisions at the world's highest center-of-mass energies. The CMS physics program is extremely broad and includes: investigating the properties of a Higgs-like boson at a 125 GeV, investigating the properties of the top quark, searching for new heavy gauge bosons, probing quark and lepton substructure, and searching for supersymmetry and extra dimensions.

On July 4, 2012, both CMS and ATLAS experiments announced the observation of a new boson state at a mass of about 125 GeV consistent with the standard model Higgs Boson. Its detailed properties are under investigation and whether this boson state is indeed the Standard Model Higgs Boson remains an open and important question.

The Maryland group continues to take leadership responsibility in the CMS experiment and for hadron calorimetry (HCAL) in particular. Prof. Hadley is the US CMS Collaboration Board Chair. Professors Baden, Eno and Skuja as well as Dr. Kellogg are involved in various aspects of HCAL operations and all phases of HCAL upgrade activities. In physics, the Maryland group has worked on a search for first and third generation leptoquarks, and the search for stopping Heavy (quasi-) Stable Charged Particles (stopping HSCP) including heavy gluinos and stops. We have also made many contributions to the measurement of the top cross-section at LHC energies.

3.1 Maryland faculty and physicists on CMS

Professor **Nick Hadley** was elected US CMS Collaboration Board Chair (USCMS CB Chair) in July 2008 and was reelected for two additional two year terms in 2010 and 2012. This is the highest elected position in US CMS. As the US CB chair, Prof. Hadley also sits on the CMS Management

Board representing US physicists and institutions. When his term ends in 2014, he plans to transfer his efforts to the calorimeter upgrades. In physics, he worked on the measurement of the top quark pair production cross section and is now focusing on searches for new physics involving the third generation.

Prof. **Drew Baden** has the overall responsibility of designing, constructing and maintaining the Trigger/DAQ electronics for the CMS HCAL. Prof. Baden is also the HCAL Upgrade coordinator for the HCAL Phase I upgrade. The phase I upgrades include a replacement of all HCAL photodetectors as well as all electronics. He has worked on searches for leptoquarks.

Dr. **Richard Kellogg** was responsible for the installation and commissioning of the HCAL Trigger/DAQ electronics system at CERN. Dr. Kellogg is also the HCAL operations expert for all of the HCAL electronics at CERN, including the front-end electronics designed and manufactured by FNAL.

Prof. **Sarah Eno** has held many physics analysis related positions on CMS. She was the physics coordinator for the Jets and Missing E_t physics working group for CMS until Fall of 2002. In 2004, Prof. Eno become the co-head of the Fermilab LHC Physics Center (LPC) along with Dr. Avi Yagil of FNAL (now at UCSD). In 2006 she became the co-head of the CMS SUSY and the Physics Beyond the Standard Model group at CERN. This coordination position morphed into the coordination of the CMS Exotica Group in 2009. At present she coordinates the HCAL Missing Transverse Energy (MET) working group in the QCD jet group and is a member of the CMS publications committee. She is also participating in the replacement of the photodetectors for the forward hadronic calorimeter (HF) and on designs for phase II calorimetry upgrades.

Prof. **Andris Skuja** is the longest serving member of Maryland on CMS. He led the Maryland effort on CMS in its formative years. He wrote the US CMS constitution (along with Jay Hauser and Dan Green) that served US CMS from 1998 until 2009. Prof Skuja was the International CMS HCAL project Manager and a member of the CMS Management Board (mid 2006 to mid 2009). He had overall CMS responsibility for installation and commissioning of HCAL during the crucial commissioning years before LHC startup. Currently, he works on long lived quasi stable particle searches as well as helping coordinate the outer hadron calorimeter photodetector replacement with SiPMs. He is one of four members of the HCAL Advisory Board and a member of the HCAL Executive Board. In 2011 he helped coordinate the HCAL service work and was a member of the group charged with amending the HCAL subdetector constitution.

Post-doc Dr. **Jeff Temple** managed the DQM (Data Quality Monitoring) group for the HCAL DPG (Detector Performance Group). He worked on the search for quasi stable particles as well as on the top quark production cross-section. He also is the lead author of the framework code for managing algorithms for identifying and flagging anomalous energies. In 2011 Dr. Temple implemented the CMS remote site at Maryland for CMS computer monitoring shifts.

Post-doc Dr. **Paolo Rumerio** was in charge of the HCAL Operations Team until the end of 2010. He led this effort for two years. He was a key person in maintaining the CMS HCAL in running condition during the LHC start-up years. He worked on the search for first generation leptoquarks. He became an Assistant Professor at the University of Alabama in early 2012.

Post-doc Dr. **Francesco Santanastasio** led the HCAL prompt feedback group until the end of

2010. He worked on leptoquark searches while at Maryland. He was one of the key players in commissioning of MET and in developing algorithms for the removal of noise in the HF detector. He became a CERN Fellow in the fall of 2011.

Post-doc Dr. **Ted Kolberg** works on HCAL monitoring as well as a stop search. His HCAL activities have focused on preparing the sub detector for 2012 data-taking, taking shifts as the Detector On Call (DOC) for the HCAL, and leading the HCAL Detector Monitoring Group (DMG) which produces long-term analysis of the stability of HCAL gains, timing, and performance.

Post-doc Dr. **Matthieu Marionneau** works on missing E_T and Particle flow, off line HCAL DQM and a third generation leptoquark search as well as an R-parity violating Stop search.

Four Maryland graduate students received their Ph.D's in 2010-11 on CMS. These students are Dr. Ellie Twedt (now a postdoc working on Maryland Babar program), Dr. Malina Kirn (now working at the Palantir corporation), Dr. Ken Rossato (now working at the Amentra corporation) and Dr. Dinko Ferncek (now a post-doc at Rutgers University). At the end of this grant period we had four grad students working on CMS – Christopher Anelli, Brian Calvert Kevin Pedro, and Young Shin. Mr. Anelli was also supported by Professor Belloni's start-up funds.

The Maryland Physics department group is joined by the heavy ion group from the Maryland Chemistry Department consisting of Professor Alice Mignerey and research scientist Dr. Marguerite Tonjes as well as a number of graduate students. Dr. Tonjes helps maintain the CMS Tier 3 computer facility at Maryland. Professor Mignery's group is supported by the DOE Office of Nuclear Physics.

The University of Maryland also hosted a number of CMS visitors – in particular Emeritus Prof. Tom Ferbel (Rochester), Emeritus Prof. Suresh Tonwar (TIFR) as well as Dr. P.K. Wiliams (DOE). Emeritus Professor C. Y. Chang of Maryland also joined the group on occasion.

3.2 The LHC at CERN

The Large Hadron Collider at CERN is a proton-proton collider with a center-of-mass energy ranging from 900 GeV to 14 TeV. The construction of the LHC finished in the summer of 2008 and startup of the machine occurred in early September of that year. Unfortunately the first week of success was followed by an incident which shut down the collider for a year. The recovery from the incident and the installation of additional safety systems to ensure that similar events would not occur again took more than a year. The subsequent LHC startup began in November 2009 at a center-of-mass energy of 900 GeV. After a further period of testing, the LHC reached a center of mass energy of 7 TeV on March 30, 2010 with only 2 bunches in the machine. The number of bunches and the number of particles per bunch gradually increased during 2010 and 2011. The maximum instantaneous luminosity obtained in 2011 was approximately 4×10^{33} cm^{-2} sec^{-1} while an integrated luminosity of 5.6 fb^{-1} was recorded in 2011. Collisions continued in 2012 at a center of mass energy of 8 TeV. An additional 21 fb^{-1} at 8 TeV have been delivered to CMS by the LHC by the end of December of 2012. When performing well, the LHC delivered 1 fb^{-1} per week.

CMS has observed a new bosonic state at 125 GeV that is consistent with the Higgs boson. Collisions continued until March of 2013 for heavy ion running. The heavy ion run has been followed by a shutdown expected to last 18 months (LS1) for LHC machine improvements. Upgrades will also be made to the CMS detector during that time.

3.3 The CMS Detector

The CMS detector is designed to exploit the full range of physics at the LHC up to the highest luminosities. The detector silicon-based tracking and calorimetry components are situated in a high-field (3.8T) superconducting solenoid, leading to a compact design for the muon spectrometer. Identification of muons, photons and electrons with an energy resolution of 1% over a large momentum range was emphasized in the design considerations. Hadron calorimetry (HCAL) is essential to the measurement of jets and missing E_T. In addition, CMS has developed the particle flow (PF) analysis methodology that identifies calorimeter clusters with particle tracks in the CMS Silicon Tracker yielding a much better energy resolution than one could obtain by the stand alone calorimeter measurements.

3.4 Maryland CMS Tier 3 Computing Cluster

The CMS computing structure is organized in Tiers, starting with Tier 0 at CERN. The individual university tiers are Tier 3 computing centers, under the management and organization of the local physics groups.

The University of Maryland Tier 3 Cluster currently consists of three management nodes, 160 cores, 232 batch slots, 2 interactive nodes, and 75 TB of usable disk.

Our cluster has been a very productive. There are currently 58 Tier 3 sites registered with CMS, of which 28 are in the US. Maryland was in the top 5 among all Tier 3s in both number and fraction of successfully completed jobs in 2010. In 2011, our average efficiency for good jobs was 91.7% , and our Tier 3 processed over 90 million events, corresponding to 2772 days of CPU time, and an average 48 jobs/day. Given the difference in computing resources and personnel resources at many Tier 3 sites and our Tier 3, the hard work of our Tier 3 team has paid off in performance.

3.5 Maryland's Contributions to CMS Physics Results

The Maryland CMS group has made strong contributions to CMS physics publications. We have concentrated on the following topics: a measurement of the top quark cross section — one of the dominant backgrounds for new particles searches, a search for first generation leptoquarks — a search suitable for first data, novel searches for the supersymmetric partner of the stop quark (stop, $\widetilde{t}$) – both long-lived and R-parity-violating (RPV), and commissioning of one of the most probable signatures of new physics — missing transverse energy. The RPV-stop result has also been interpreted in terms of third generation leptoquarks, and the long-lived stop result in terms of other potential long-lived heavy charged particles. Our contributions to management and papers are detailed below. The results are then described in detail, including associated work on detector-related software that enabled the results. We also describe our near-term plans for physics analysis.

A list of internal CMS notes co-authored by members of the Maryland CMS group is included in the appendices.

Maryland is one of the leading groups in the CMS "Exotica" physics analysis group, which concentrates on searches not related to the Higgs boson or to R-parity conserving SUSY. Sarah Eno was a co-convener of the Exotica group from 2006 to 2008 and is currently a member of the Exotica subgroup of the CMS publications committee. She was co-convener of the subgroup of the Exotica group concentrating on leptoquarks from 2009 to 2011. Paolo Rumerio became a co-convener of this group in 2011.

Malina Kirn, Jeff Temple, and Nick Hadley contributed to the CMS paper (Phys. Rev. **D84** 092044 (2011)) on the measurement of the $t\bar{t}$ production cross section using b tagging. Their contribution was an optimized analysis involving neural nets, and was the thesis research of Dr. Kirn. Temple and Hadley wrote and edited **all** of the paper on the CMS $t\bar{t}$ cross section measurement in the lepton plus jets channel using kinematic properties of the events to separate signal from background (Eur. Phys. J. C **71**, 1721 (2011)). This required the delicate politics of balancing the seven separate CMS analyses from all the different groups that measured this cross section.

Ellie (Lockner) Twedt, Paolo Rumerio, Dinko Ferenček, Francesco Santanastasio, Sarah Eno, and Drew Baden wrote a paper (Phys. Rev. Lett. **106** (2011) 201802) on a search for leptoquarks decaying to two electrons and two jets using 33 pb^{-1} of data. This was the thesis dissertation topic of Dr. Twedt. Ferenček, Santanastasio, and Eno wrote another paper (Phys. Lett. B **703**, 246 (2011)) on a search for leptoquarks decaying to an electron, a neutrino, and two jets using 36 pb^{-1}. This was the thesis dissertation topic of Dr. Ferenček. For his contributions to this research, then Maryland postdoc (now Assistant Professor at Alabama) Paolo Rumerio was appointed to co-convene the "Leptons plus Jets" subgroup of the CMS Exotica group.

Kenneth Rossato, Andris Skuja, and Sarah Eno, with colleagues from other institutions, wrote a paper (Phys. Rev. Lett. **106** 011801 (2011)) on a search for long-lived gluinos using 10 pb^{-1} of data. This was the thesis research of Dr. Rossato. Jeff Temple and Andris Skuja were among the main authors of the updated results using 886 pb^{-1} that also extended the result to include long-lived stops (arXiv:1207.0106, submitted to J. High Energy Physics).

Matthieu Marionneau, Keti Kaadze (CERN), and Sarah Eno have performed a search for an RVP stop that decays to a tau and a b. The result is public (CMS public document PAS CMS-EXO-12-002). The paper is currently under collaboration-wide review and submission to a journal will follow.

Sarah Eno was the leader of a group of authors of a paper evaluating the performance of the reconstruction of missing transverse energy ($\not{E}_T$) with the CMS detector (JINST **6**, P09001 (2011). She was also the paper's editor. This work was enabled by our extensive contributions to algorithms for understanding sources of anomalous energy in the HCAL (noise) and work on HCAL monitoring and calibration, which are described in the section on the $\not{E}_T$ results.

MD group members have also contributed to the internal reviews of many CMS publications. Prof. Baden served on the internal review for two papers: a search for compositeness in dijet events using an angular variable, and a measurement of dijet azimuthal correlations. Nick Hadley chaired the internal review for a search for a fourth-generation charge -1/3 quark, the internal review committee for the CMS luminosity measurement, a measurement of the top cross section in the all-jets final state, and a search for flavor changing neutral currents in top quark decay. Sarah Eno chairs three internal review committees: a search for excited electrons (muons) decaying to an electron (muon) and a photon, a search for a heavy, weak, charged vector boson decaying to a top and a b, and a search for unparticles produced in association with a Z boson. She also served on the internal review for a search for the first paper on squarks and gluinos decaying with a jets and $\not{E}_{\mathrm{T}}$ signature. Paolo Rumerio served on the internal review committee for a search for a heavy neutral gauge boson decaying to two electrons or two muons.

3.5.1 Measurement of the pair-production cross section for top quarks

Kirn, Temple and Hadley have performed a measurement of the $t\bar{t}$ cross section using a multi-layer perceptron neural network to distinguish $t\bar{t}$ signal events from backgrounds after requiring a muon and three jets passing the selection criteria. The neural network comprises two hidden layers, with the first layer containing five nodes and the second containing four nodes. Three kinematic variables are passed into the neural network: the pseudorapidity $|\eta^{\mu}|$ of the muon, the distance ΔR_{12} in $\eta - \phi$ space between the two highest-p_T jets in the event, and a boolean indicating the presence of at least one b-tagged jet. The distribution of these variables in both data and various Monte Carlo samples is shown in Figure 3.1.

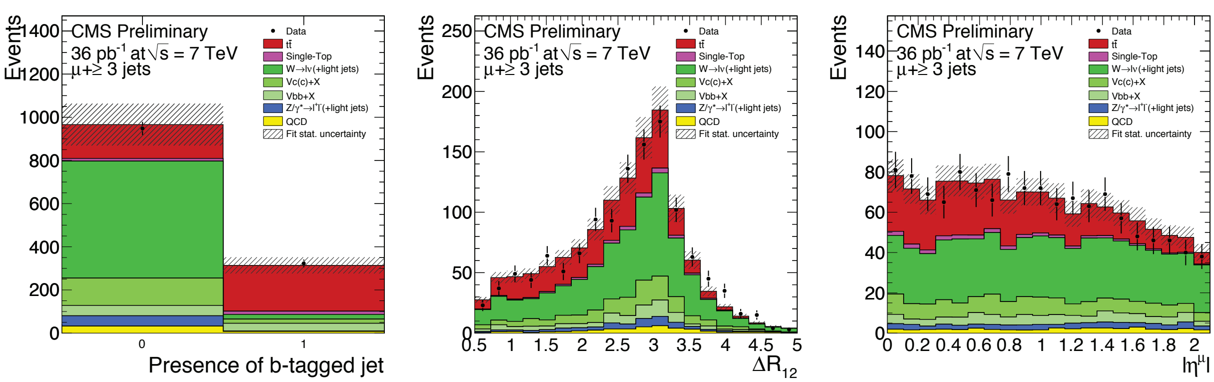


Figure 3.1: Inputs to the neural network for Monte Carlo and data, where Monte Carlo event yields and statistical uncertainties are taken from the fit to the data: (left to right) b tag boolean, ΔR_{12}, $|\eta^{\mu}|$.

Monte Carlo signal and background samples are used to train the neural network. Discriminators are generated for the signal and background samples, and are fit to the data. The result of this fit provides the number of $t\bar{t}$ events present in the data, and the $t\bar{t}$ cross section is extracted from this value. A signal discriminator is generated from the Monte Carlo $t\bar{t}$ sample. Corrections are applied to both $t\bar{t}$ and single top simulated events to account for observed differences between the jet energy resolution measured in data and the resolution in the simulated samples. An additional flavor-dependent correction is applied to the Monte Carlo-generated jets to account for differences in b tagging rates between data and simulation. Discriminator shapes for QCD, $W+$ jets, and $Z+$ jets are produced directly from data. QCD events are selected by applying the nominal selection cuts, but reversing the isolation cut to require that selected muon has a combined relative isolation greater than 0.1. Background discriminators for W and Z are generated from data in a similar manner, by applying the nominal selection with the revised requirement that only two jets with $p_T > 30$ GeV/c are present in the event. Predictions from Monte Carlo simulations indicate that QCD events make up 97% of the events passing the reverse muon isolation cut, and that 87% of events in two jet events come from W or Z processes, validating the use of these cuts in determining their respective templates.

The fit of the neural net discriminants to events passing selection cuts in 36.1 pb^{-1} of 2010 collision data is shown in Figure 3.2. The result of the fit indicates a signal yield of 369 $\pm$ 36 (stat.) events, corresponding to a $t\bar{t}$ cross section of 151 $\pm$ 15 (stat.) pb.

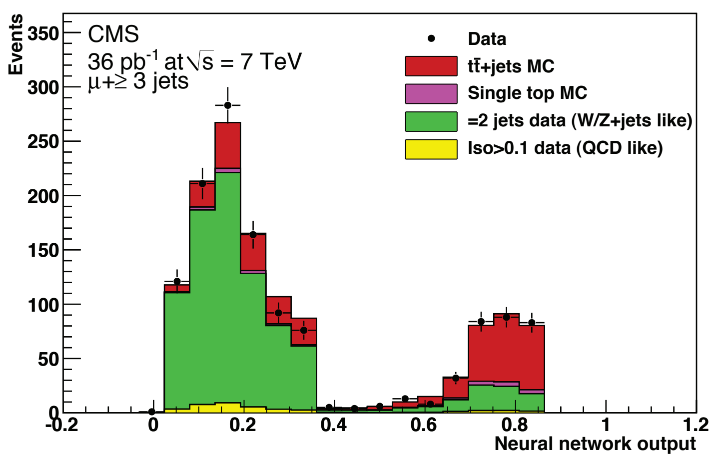


Figure 3.2: Results of template fit to the discriminant calculated from 36.1 pb^{-1} of data.

Overall systematic uncertainties in the cross section are evaluated by shifting simulated events by the appropriate systematic error. The resulting pseudo-data is fit with the nominal discriminator templates for $t\bar{t}$ and single top and systematically shifted templates for QCD and $W/Z+$ jets since these templates are derived from data. The dominant cross section systematic $(+16\%/-15\%)$ arises from uncertainties in the b tagging efficiencies. When combined with the remaining systematic effects, the overall systematic uncertainty is found to be $(+23\%/-18\%)$. An additional 4% systematic arises from uncertainty in the recorded integrated luminosity, resulting in a $t\bar{t}$ cross section measurement of 151 $\pm$15 (stat.) $^{+35}_{-28}$ (syst.) $\pm$6 (lumi.) pb. This result was included in the CMS paper on the $t\bar{t}$ cross section with b tagging (Phys. Rev. **D84** 092044 (2011)).

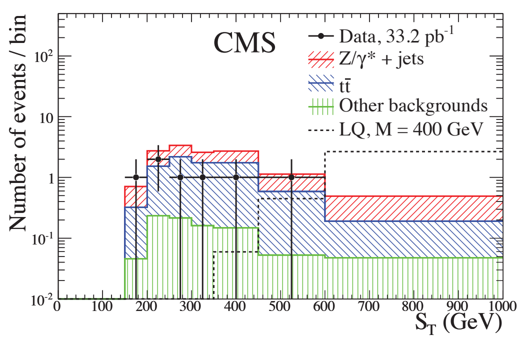
3.5.2 Search for first generation leptoquarks

Leptoquarks (LQs) are bosons that couple to lepton-quark pairs. Bosons with such couplings occur in Grand Unified Theories that embed the quark and leptons of the Standard Model into a single unification group at high energies, composite models, and some types of supersymmetry with r-parity violation. Those from supersymmetry would naturally have mass of a few hundred GeV.

Precision low-energy experiments such as searches for flavor changing neutral currents and leptonic pion decay strongly constrain LQs that couple different generations and searches for proton decay constrain them to be baryon and lepton number conserving [1]. A LQ decays either to a charged lepton and a quark or a neutrino and a quark. The fraction of decays to a charged lepton can be taken as a free parameter (β), although β is either 0, 0.5, or 1 in most models. Since LQs are colored, the cross section for pair production of leptoquarks via gluon-gluon fusion at a proton machine is large. The Maryland CMS group has completed two searches for first-generation LQs using the 36 pb^{-1} of the 2010 run.

In the first search, we look for events containing two high-P_T electrons and two high-P_T jets. To remove backgrounds from associated production of the Z boson with jets, we veto events with a di-electron mass less than 125 GeV. We also require the scalar sum of the P_T of the two leading electrons and two leading jets (S_{T}) be large, as this reduces the remaining backgrounds, such as $t\bar{t}$ production and multi-jet events with two jets mis-identified as electrons. Figure 3.3 (left) shows the S_{T} distribution observed in data before the final S_{T} cut. There is good agreement with the background prediction and so limits are set on the leptoquark production cross section times β^2. Figure 3.4 (left) shows the resulting limit. Figure 3.4 (right) shows the resulting mass limit when the results are combined with those of the second analysis.

In the second search, we look for events containing a high p_{T} electron, large $\not\!\!E_{\mathrm{T}}$, and two high-p_{T} jets. To remove backgrounds from associated production of the W boson with jets, we require the transverse mass, defined $M_T = \sqrt{2 \cdot p_{\mathrm{T}}(e) \cdot \not\!\!E_{\mathrm{T}}(1 - \cos\Delta)}$, where Δ is the opening angle in ϕ between the electron and the $\not\!\!E_{\mathrm{T}}$, to be larger than 125 GeV. We also require the S_{T}, defined as the scalar sum of the p_{T}s of the electron, the $\not\!\!E_{\mathrm{T}}$, and the two leading jets, to be large. Figure 3.3 (right) shows the M_{t} distribution before the M_{t} requirement and with just a loose S_{T} requirement. Again good agreement is seen between data and the background-only hypothesis. Figure 3.4 shows the limit on the leptoquark mass versus β from the combination of this search and the eejj search.



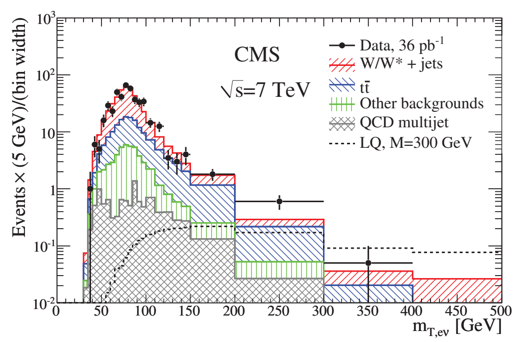


Figure 3.3: On the left: for the eejj analysis, the S_{T} for the MC distributions for the signal ($\beta = 1$, M= 400 GeV) and the contributing backgrounds. Other backgrounds include W+jets, di-boson, and single top. All background histograms are cumulative. On the right: for the eνjj analysis, the M_{t} distribution for events that have passed the eνjj preselection requirements. The MC distributions for the signal ($M_{\mathrm{LQ}} = 300\mathrm{GeV/c}^2$, $\beta = 0.5$) and the contributing backgrounds are shown.

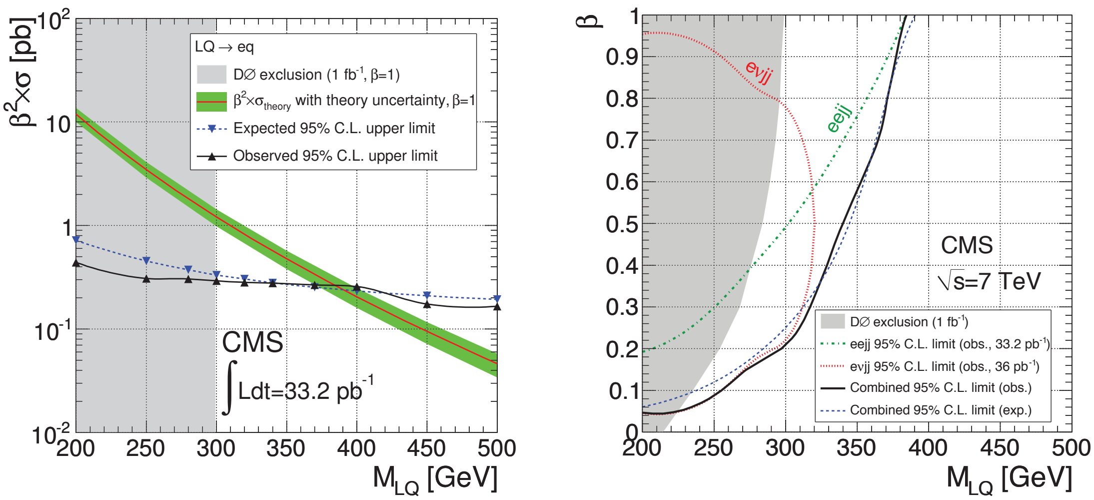


Figure 3.4: On the right: for the eejj analysis, the expected and observed upper limit at 95% C.L. on the LQ pair production cross section times β^2 as a function of the LQ mass. On the left: for the eνjj analysis, observed exclusion limits at 95% CL on the first generation LQ hypothesis in the β versus LQ mass plane using the central value of signal cross section, for the individual eejj and eνjj channels, and their combination.

3.5.3 Searches for stop quarks

Before the start of LHC running, many physicists hoped that the resulting data would provide answers to several long-standing puzzles in fundamental physics: Is the existence of a Higgs boson with a mass on the order of the weak scale really what allows massive bosons in an $SU(2)_L \times U(1)_Y$ gauge-invariant quantum field theory? If so, is the weak-scale mass really due to a remarkable cancellation between a large bare mass and large radiative corrections, or is there some symmetry or other mechanism that reduces the radiative corrections? If it is a symmetry, is it supersymmetry? And is the dark matter that is needed to explain several cosmological observations the lightest supersymmetric particle of supersymmetry with an additional symmetry, R-parity, which makes this particle stable?

The current LHC and Tevatron data show a new boson consistent with a weak-scale (125 GeV) Higgs boson. However, there is currently no sign of supersymmetry through searches with signatures consistent with R-parity conservation [2, 3]. Perhaps the Higgs boson is the only new physics accessible at the TeV scale. However, weak-scale supersymmetry is not ruled out. The most problematic portion of the radiative corrections comes loops involving the top quark. And there are sensible solutions to the dark matter problem that do not require supersymmetry (for example:

the axion of QCD). If dark matter problem and the hierarchy problem are decoupled, as suggested in [4], [5], R-parity-violating (RPV) [7] and other novel forms of SUSY start to be appealing[6].

At the LHC, a stop and an anti-stop pair can be produced via strong interactions. When the mass of the supersymmetric partners of the gluon and quarks, excluding top quark, are large, the stop anti-stop pair pair production cross section is similar to that of the third generation scalar leptoquarks. The cross section also depends on the first generation squark mass and the stop mixing angle due to the loop-corrections, but contribution from these processes is less than two percent.

The large mixing angle (θ) between the left-chiral and right-chiral stops ($\widetilde{t_L}$ and $\widetilde{t_R}$) due to the large top Yukawa coupling can produce two mass eigenstates, $\widetilde{t_1}$ and $\widetilde{t_2}$, with $M_{\widetilde{t_1}} < M_{\widetilde{t_2}}$. $M_{\widetilde{t_1}}$ can be smaller than the masses of the other scalar SUSY particles.

The Maryland group has looked for stop quarks with two novel signatures: long-lived stops and stops with RPV decays. The two are connected: the lifetime for stops in RPV SUSY is set by the size of the RPV coupling constants. When the coupling is very small, the first search has sensitivity when the stop is the lightest SUSY sparticle, when larger, the later. (In addition to a small RPV coupling, there are also other ways to produce long-lived stops.) These searches can also be interpreted in terms of other long-lived heavy particles and in terms of third-generation leptoquarks respectively.

Search for long-lived stops and other long-lived heavy particles

We have searched for a long-lived stop quark. However, more generally, heavy, long-lived particles are predicted in a wide variety of theories of physics beyond the standard model. One such particle that may be produced with a large cross section is the gluino in "split supersymmetry" models'[8]. In these models, the gluino decay is suppressed due to the large gluino-squark mass splitting, extending the gluino's lifetime.

If the heavy colored particle is produced with a relatively slow speed ($\approx \beta$ <0.3), the energy loss due to ionization in the CMS detector can be large enough that the particle comes to rest within the detector material. Eventually, the particle decays and the resulting decay products can produce jet-like signals in the detector.

Physicists from Maryland (Temple, Eno, Skuja, Rossato) along with colleagues from the CMS collaboration, have searched for signs of such particle decays during times when there are no collisions in the detector. We perform this search using data taken in 2011 with a total integrated luminosity of 4.0 pb^{-1}, corresponding to 246 hours of trigger live time. During the 2011 running, the bunches collided at intervals as small as 50 ns, with the detector readout clocked at 25 ns. We searched in the empty cycles as well as during larger gaps in the beam structure that exist to facilitate beam dumps and beam injections. Figure 3.5 shows the resulting accumulation of particles in the detector material during collisions times and the exponential decay during beam off periods for a gluino with a 1 μs lifetime for data taking with 140 colliding bunches.

We select events using a trigger that requires a calorimeter jet above a certain energy threshold. We restrict our search to the central ($|\eta| < 1$) region of the calorimeter. We veto on signals in the beam pickup monitors, and reject events that occur within 50 ns of any filled bunches.

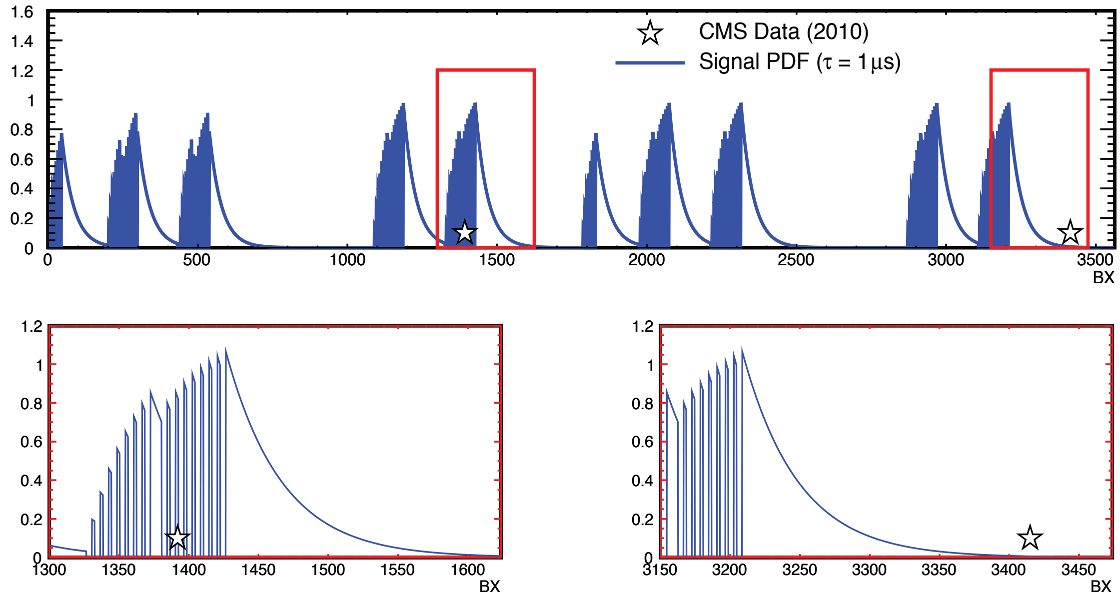


Figure 3.5: The top panel shows the in-orbit positions of 2 observed events in the subset of our data that was recorded during an LHC fill with 140 colliding bunches. The decay profile for a 1 μs lifetime hypothesis is overlaid. The bottom panels are zoomed views of the boxed regions around the 2 events in the top panel so that the exponential decay shape of the signal hypothesis can be seen.

The main backgrounds are cosmic rays, beam-halo muons, beam-gas interactions of non-colliding bunches, and discharges of the hybrid photodiodes (HPDs) and readout boxes (RBXs) that are used in the HCAL readout. Since 18 HCAL channels with the same ϕ value are read out using the same HPD, and since each RBX reads out signals from HPDs in 4 adjacent ϕ bands, HCAL discharges produce distinctive geometric patterns of energy deposition in the calorimeter. The discharges also produces distinctive pulse shapes. This shape and geometry information is used to reject events containing electronics noise. We also use information from the muon detectors to reject cosmic ray events. The rate of residual noise and cosmics events that pass the selection criteria is measured from runs in the 2010 data sample with low instantaneous luminosity.

The number of observed events is consistent with background expectations, and thus limits on the production cross section times branching fraction as a function of lifetime are set. The resulting limits on stops and gluinos are shown in Fig. 3.6. For a gluino decay with visible energy greater than 100 GeV, and assuming that the branching fraction of the gluino to a gluon and the lightest neutralino is 100%, gluinos with mass less than 642 GeV are excluded for lifetimes from 10 μs to 1000 s. Stop squarks with masses less than 343 GeV are excluded for the same lifetime range, assuming visible energy greater than 200 GeV in the stop decay.

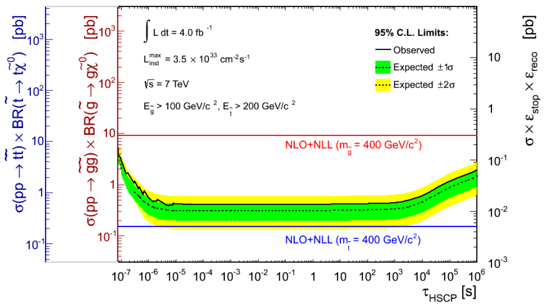


Figure 3.6: Expected and observed 95% C.L. limits on stop and gluino pair production cross section times branching fraction using the "cloud model" of R-hadron interactions as a function of particle lifetime. The right-hand axis shows the model-independent 95% C.L. limit on particle production cross section × branching ratio × stopping probability × reconstruction efficiency.

RPV stops

Trilinear R-parity violating operators allow the lepton-number-violating decay $\widetilde{t_L} \to \tau$b [7] with partial width proportional to the RPV coupling λ'_{333}. Third generation leptoquarks can also have this decay, with similar kinematics.

The search by Marionneau and Keti Kaadze (CERN) (with contributions by S. Eno) for $pp \to LQ_3 L\bar{Q}_3 \to b\tau b\tau \to b\ell b\tau_h$, where τ_h is a hadronically-decaying τ and ℓ is a muon or an electron, uses the full 5 fb^{-1} collected by the CMS detector during 2011. The main irreducible backgrounds are $t\bar{t}$ production, WW production, and $Z \to \tau\tau$+jets. Important instrumental backgrounds include W + jets with a fake τ and multi-jet production with a fake ℓ and a fake τ. Backgrounds are reduced through requirements on the invariant mass of the hadronically decaying τ with the b quark (using the b quark that minimizing the difference between its mass with the τ_h and the mass of the other b quark with the ℓ) and through requirements on S_T, the scalar sum of the p_{T}'s of the ℓ, τ_h, and two b jets. No excess is seen over standard model expectations, as shown in Fig. 3.7. The resulting limit is shown in Fig. 3.8

3.5.4 Commissioning of missing transverse energy and other work in the CMS Jets and Missing Transverse Energy group

Sarah Eno was the first convener of the CMS jets and missing transverse energy group (1999-2002), and Maryland has continued its tradition of strong contributions in this physics object group of the CMS experiment.

Contributions to missing transverse energy

Missing Transverse Energy is the key to the discovery of the dark matter particle if it is created in LHC collisions. A detailed understanding of the resolution and scale for missing transverse energy is also needed for searches for the Higgs boson and studies of the production properties of top

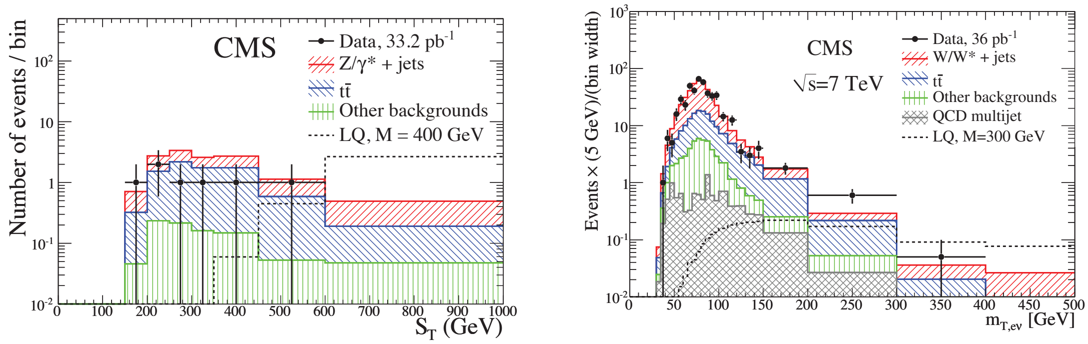


Figure 3.7: On the left: S_{T} distribution for the $\mu-\tau$ final state from the third generation leptoquark search analysis On the right: Expected and observed preliminary limit on pair production of third generation leptoquarks for 100% branching fraction to τb.

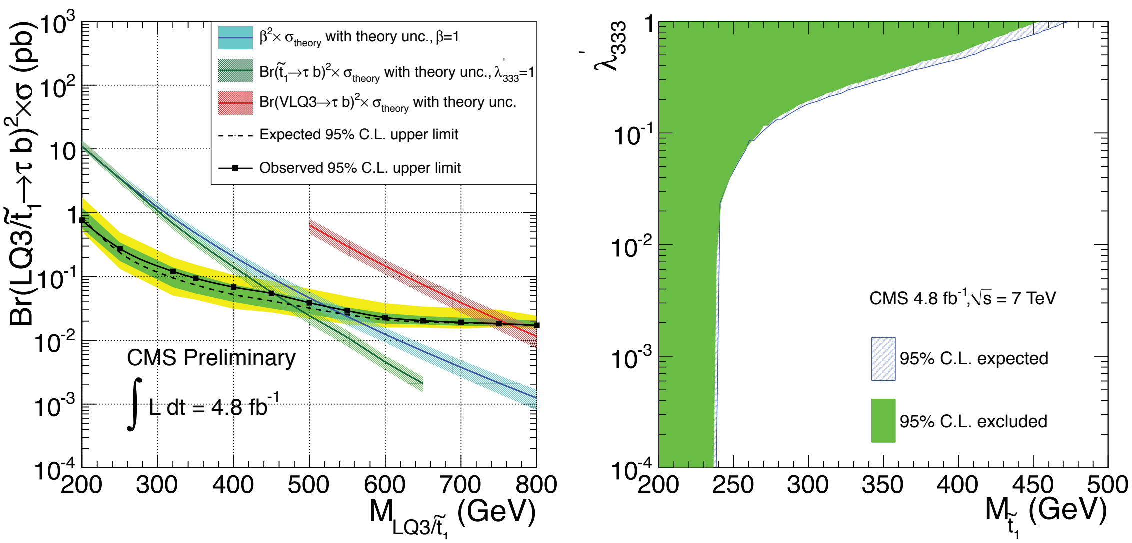


Figure 3.8: On the left: The expected and observed upper limit at 95% CL on the stop or LQ pair production cross section times branching ratio as a function of mass. On the right: limit on the RPV coupling λ'_{333} for within the minimal supersymmetric extension of the standard model with parameters $\tan\beta$=40, a higgsino mass μ of 380 GeV, stop mixing angle of zero, and the mass parameter associated with the gaugino (M_2) large ($M_2 \geq 1$ TeV).

quarks and W bosons. Sarah Eno was co-head of the missing transverse energy subgroup during the LHC turn-on years of 2009 and 2010 (along with Teruki Kamon of Texas A&M during 2009 and Kenichi Hatakeyama of Baylor University during 2010) of the CMS Jets and Missing Transverse Energy group.

CMS currently has several different methods for calculating missing transverse energy. Raw Calo $\not\!\!E_{\rm T}$ uses uncorrected calorimeter energies, and is the most basic measurement. TC $\not\!\!E_{\rm T}$ uses tracks to correct the response of the charged hadrons. PF $\not\!\!E_{\rm T}$ ("particle flow MET") does a full reconstruction of all the individual final-state particles, which are then used in the $\not\!\!E_{\rm T}$ calculation. Additional corrections are available for both Calo $\not\!\!E_{\rm T}$ and PF $\not\!\!E_{\rm T}$. The Type-I correction uses jet enery scale corrections to improve estimation of the contribution to $\not\!\!E_{\rm T}$ from jets. Type-II-corrected $\not\!\!E_{\rm T}$ includes a correction for the response for particles not clustered into jets.

During the data-taking at 900 and 2360 GeV during December of 2009 and 7 TeV running during 2010, the commissioning of this measurement was done by Santanastatio, Ferenček, Eno, and many others. The commissioning work was documented three public CMS documents, JME-10-002, JME-10-004, and JME-10-005. Santanastatio, Ferenček, and Artur Apresyan of Caltech were the primary authors on the contributing note on the commissioning of raw Calo $\not\!\!E_{\rm T}$ (CMS-AN2010/029). They studied the stability of the MET measurement, identified various types of calorimeter noise, decided (along with other collaborations) how to best use existing noise- removal algorithms in the MET calculation, and studied the various contributions of noise and the different subdetectors to the MET measurement in real time as the data came in.

All types of MET reconstruction are very sensitive to any detector malfunctions. The Maryland group has played a strong role in algorithms for identifying and removing these detector artifacts. Santanastasio is the primary author of AN-2010219, "Results of a visual scan of high $\not\!\!E_{\rm T}$ events in 7 TeV pp collision data", which helped identify the sources of anomalous high $\not\!\!E_{\rm T}$ events. Santanastasio, Temple, Ferenček (along with CMS collaborators Vodopiyanov, Gavrilov and Chlebana) are the authors of algorithms to remove one of the main sources of anomalous energies, scintillation and Cherenkov light produced in the phototubes used in the HF calorimeter. Their work is documented in the CMS internal note DN-2010008. Figure 3.9 shows the $\not\!\!E_{\rm T}$ spectrum before and after removal of anomalous energies, showing the importance of the cleaning.

Sarah Eno has also lead an international team aimed at understanding the response and resolution of the $\not\!\!E_{\rm T}$ measurement. The methodology is to use events containing an isolated high $p_{\rm T}$ photon or a Z boson decaying to electrons or muons. While these events contain no genuine $\not\!\!E_{\rm T}$, it can be induced by removing the boson. Comparing the boson $p_{\rm T}$ to the induced $\not\!\!E_{\rm T}$ allows the extraction of the resolution and scale.

At current LHC luminosities, the beam currents are large enough that there can be more than one pp scattering per bunch crossing. These "pileup" events have a deleterious effect on the $\not\!\!E_{\rm T}$ resolution. Figure 3.10 shows the resolution for different numbers of pileup interactions as measured in $Z \to \mu^+\mu^-$ events.

Maryland group members currently active in the MET group are Brian Calvert and Ted Kolberg (working on studies using the photon data sample) and Matthieu Marrioneau (using the $Z \to \mu\mu$ sample).

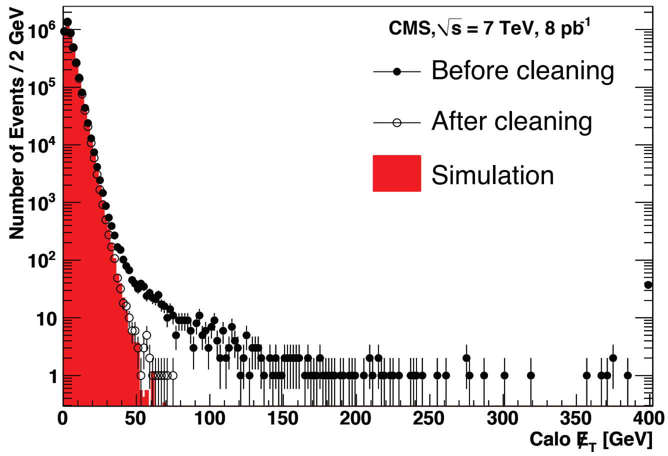


Figure 3.9: Calo $\not\!\!E_{\mathrm{T}}$ distributions in a minimum bias data sample without (black dots) and with (open circles) removal of anomalous energies, compared to simulation. Overflows are included in the highest bin.

Other Contributions to the Jets and Missing Transverse Energy Group

Dinko Ferencek, a Maryland graduate student, worked with Sarah Eno, Ia Iashvili (SUNY Buffalo), and Marek Zalinkski (Rochester) to establish the methodology for calculating the contribution from the underlying event and pileup interactions to the jet energy scale. The results were made public (CMS JME-09-003).

Ferencek, Calbert, and Peterman have all also been shifters in the CMS JETMET Data Quality Monitoring group. Ferencek wrote code that allows plots of MET-related quantities versus run number or luminosity block number.

3.5.5 Contributions to HCAL Detector Performance Group

Maryland has been a strong contributor to the software necessary for the reconstruction of energies deposited in the HCAL and rejection of false energies due to instrumental effects.

Sarah Eno co-conveneed (with Shuichi Kunori, then of Maryland) the HCAL noise task force subgroup of the HCAL Detector Performance Group during 2009. The charge was to develop and test algorithms to reject large, false energies recorded by the HCAL electronics due to discharges of their hybrid photo diodes.

Jeff Temple was the lead author of a paper on the identification and removal of HCAL noise, as studied during the cosmic ray data taking before the start of pp collisions (JINST **5** T03014 (2010)). These algorithms are still used in data reconstruction.

Jeff Temple is also the lead author and developer of the HCAL data quality monitoring system. He also is the lead author and developer of the framework for code for filtering of HCAL anomalous

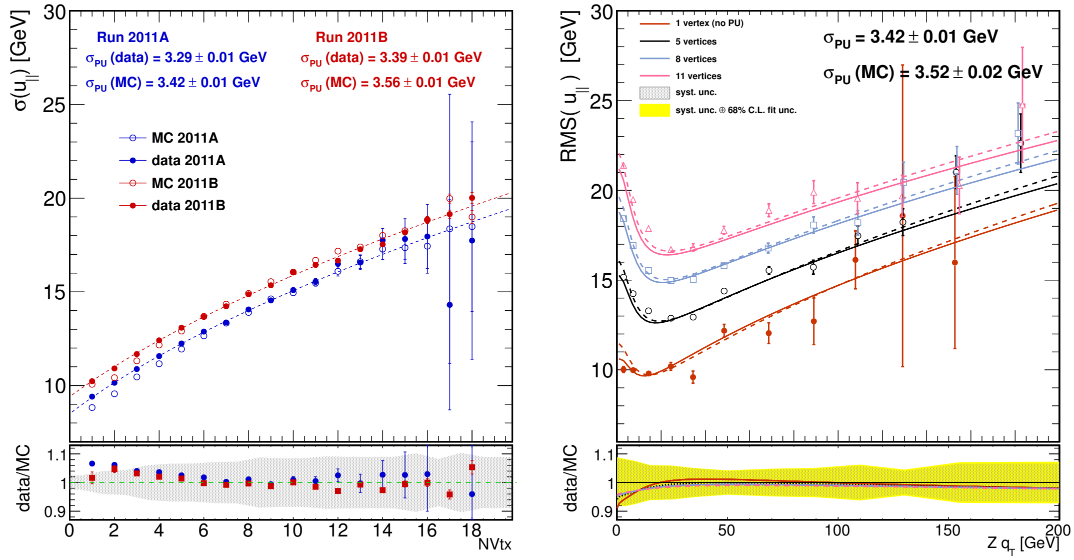


Figure 3.10: (a) Resolution of the projected recoil component along the q_T axis, as a function of the number of reconstructed vertices. The offset in resolution between the run 2011A and the run 2011B is due to larger out-of-time pileup due to the shorter bunch crossing spacing. (b) Resolution on the projected recoil component along the q_T axis, as a function of the number of reconstructed vertices and q_T. The simulation is shown as a dashed line.

energies.

3.5.6 Calibration of the Particle-Flow clusters in CMS

In CMS, the Particle-Flow technique is used to uniquely assign all signals recorded in the various detectors during a collision event to reconstructed particles (charged and neutral hadrons, electrons, muons, photons)[9]. One of the first stages in the particle reconstruction is to form clusters of calorimeter energies. In 2011, the calibration for these clusters for both data and simulation was derived from simulations of single pions, even though the response of the simulated detector was known to be different from that of the real detector [10]. The resulting mis-calibration of the neutral hadron clusters in simulation meant that different jet energy scale corrections were needed for data and for simulated events. In practice, the calibration from simulation was applied to data, and then a “residual” calibration was applied to data to correct for the miscalibration. Marionneau has obtained a calibration using isolated tracks in minimum bias events, using the measured momentum of the track as a reference. The main difficulty is getting a truely isolated sample of clusters, as contamination of the cluster energy from other near-by, soft particles biases the calibration. Another limiting factor on the calibration from data is the available statistics. Marionneau solved this by retaining parts of the calibration from simulation (how the calibration depends on the fraction of the energy recorded in the electromagnetic calorimeter, and the dependence on pseudorapidity) while getting the calibration of the portion of the energy deposted in the hadronic calorimeter from these isolated tracks.

The resulting calibration is good enough that the residual calibration is no longer necessary, as shown in Fig. 3.11. This Fig. shows the fractional difference between the Z boson p_{T} and the p_{T} of the leading jet, recoiling against the Z, when the old MC-based calibration (default), the MC-based plus residual calibration (red) and the new MC-based calibration applied to data without a residual correction (blue) when the new calibration for neutral hadrons is used. As can be seen, the residual correction is no longer needed for jets after the data-based recalibration of the neutral hadrons.

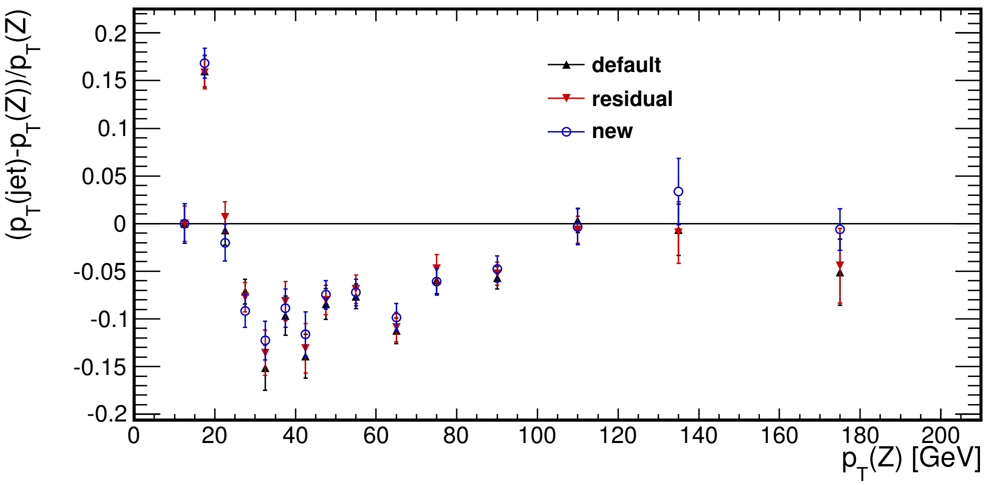


Figure 3.11: The fractional difference between the Z boson p_{T} and the p_{T} of the leading jet, recoiling against the Z, when the old MC-based calibration (default) for jets is used, the MC-based plus residual calibration (red) and the new MC-based calibration applied to data without a residual correction (blue) when the new data-based calibration for neutral hadrons is used. As can be seen, the residual correction is no longer needed for jets after the data-based recalibration of the neutral hadrons.

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Appendix A

Talks and CMS Internal Notes

A.1 Talks by Maryland Group Members 2009 - 2012

Babar and Super B Talks

1. A. Jawahery, "Experimental Summary of the 2009 Moriond Electroweak Conference", March 14, 2009, La Thuile, Italy.
2. A. Jawahery, "Physics Opportunities at a Super Flavor Factory in the LHC era", At the Meeting of the US High Energy Physics Advisory Panel (HEPAP), May 21, 2009, Washington DC.
3. A. Jawahery "Summary talk of the Conference on CP violation and Flavor Physics", Flavor Physics and CP violation, Torino, Italy, May 31, 2010.
4. A. Jawahery , "CLEO's Impact: A view from the Inside and the Outside", on the occasion of celebration of David Cassel's contributions to research and teaching", March 12, 2011, Cornell University, Ithaca, N.Y.
5. A. Jawahery, "CP Violation", Plenary talk at the 2011 Meeting of Division of Particles and Fields (DPF) of American Physical Society, Providence, RI.
6. D. Roberts, "The Status of SuperB", Annual Meeting of the IUAPAP Working Group (WG.9): Committee on International Cooperation in Nuclear Physics, Cambridge, MA, Jul 25, 2011.
7. D. Roberts, "The Physics Search Potential of SuperB", The 19th Particles and Nuclei International Conference (PANIC11), Cambridge, MA, Jul 24-29, 2011.
8. D. Roberts, "The SuperB Project", The Hunt for New Physics, from the Alps to the Plains to the Rockies, Aspen Center for Physics, Aspen, CO, Feb 11-17, 2012.
9. R. Cenci, "Charm spectroscopy at B factories", Rencontre de Moriond, QCD and High Energy interactions, La-Thuile, Italy, Mar 22, 2011.

10. R. Cenci, “SuperB detector response to background”, Joint Belle II & SuperB Background Meeting, Vienna, Austria, Feb 10, 2012.
11. B. Hamilton, “Measurements of the B_s Semileptonic Branching Fraction and B_s Production Above the $\Upsilon(4S)$”, Lake Louise Winter Institute, Canada, Feb 23, 2011.
12. B. Hamilton, “Measurements of the B_s Semileptonic Branching Fraction and B_s Production Above the $\Upsilon(4S)$”, Contributed talk, APS April Meeting, Anaheim, CA, May 2, 2011.
13. B. Hamilton, “Recent Results in Semileptonic B Decays with *BaBar*”, APS Meeting of the Division of Particles and Fields, Providence, RI, August 10, 2011.
14. E. Behn, “Search for flavor-changing-neutral-current and lepton-flavor-violating decays of the D^0 meson at BABAR”, Contributed talk, APS April Meeting, Atlanta, GA, April 1, 2012.

CMS and DØ Talks

1. P. Rumerio, “Status of the CMS Detector”, invited talk at the Conference ”The LHC and Dark Matter” at Ann Arbor, January 6-9, 2009.
2. P. Rumerio, “From Detector Commissioning and Start-up Calibration to a Search for Leptoquarks with the CMS Experiment at the LHC”, Colloquium at University of Alabama, USA, Mar 1, 2011
3. P. Rumerio, “From Detector Commissioning and Start-up Calibration to a Search for Leptoquarks with the CMS Experiment at the LHC”, Seminar at Northwestern University, USA, Feb 14, 2011
4. P. Rumerio, “From Detector Commissioning and Start-up Calibration to a Search for Leptoquarks with the CMS Experiment at the LHC”, Seminar at University of Minnesota, USA, Feb 10, 2011
5. F. Sanatanastasio, “Prospects for Exotica Searches at ATLAS and CMS Experiments”, invited talk at the conference “IFAE 2009, Bari, IT: Incontri di Fisica delle Alte Energie”, April 15-17, 2009.
6. F. Sanatanastasio, “Search with early data (jets, heavy quarks/strong forces, top,SUSY) at CMS”, invited talk at the conference ”DIS2010, Firenze, IT: XVIII International Workshop on Deep-Inelastic Scattering and Related Subjects?, April 19-23, 2010.
7. F. Santanastasio, ”Exotica Searches at CMS”, Talk in plenary session at the international conference “Rencontres de Moriond on EW Interactions and Unified Theories”, 13-20 March 2011, La Thuile, Valle D’Aosta, Italy.
8. J. Temple,“Search for long-lived particles at CMS”, Supersymmetry 2011, FNAL, September 1, 2011.

9. J. Temple,“Top results from ATLAS and CMS”,ISMD2011: XLI International Symposium on Multiparticle Dynamics, Hiroshima, Japan, September 29, 2011.
10. J. Temple, “Stopped Gluino and Longlived Charge Sparticle Searches in CMS”, Berkeley-SUSY: Workshop on Supersymmetry at the LHC, Berkeley, CA, October 19, 2011.
11. J. Temple,“Search for Heavy Stable Charge Particles at CMS”, seminar at University of Pennsylvania, November 1, 2011.
12. J. Temple,“Search for Heavy Stable Charged Particles at CMS”, seminar at Rutgers University, November 8, 2011.
13. E. Twedt, “Search for Heavy Neutrinos at CMS” invited talk at the SUSY09 conference, Boston, MA, June 6, 2009
14. E. Twedt, “First Generation Leptoquarks at CMS” talk at the APS ”April” meeting, Washington DC, Feb. 12 2009
15. M. Kirn, “The First Measurement of Top Production Cross Section”, Lake Louise Winter Institute, Canada, Feb 21, 2011.
16. D. Ferenček, “Search for Pair Production of First-Generation Scalar Leptoquarks with the CMS Experiment at CERN”, invited Seminar at Rutgers, The State University of New Jersey, May 31, 2011.
17. D. Ferenček, “Search for Pair Production of First-Generation Scalar Leptoquarks in *pp* Collisions at $\sqrt{s} = 7$ TeV”, talk at the APS April Meeting, Anaheim, CA, May 1, 2011.
18. D. Ferenček, “Results of a Search for Pair Production of First-Generation Scalar Leptoquarks in *pp* Collisions at $\sqrt{s} = 7$ TeV”, talk at the USLUO Annual Meeting, Fermilab, Oct. 30, 2010
19. N. Hadley, “The CMS Experiment at the LHC: The Good, the Bad, and the Ugly”, invited talk at the annual meeting of the Maryland Chapter of Sigma Xi, May 12, 2009.
20. N. Hadley, “Searching for Boosted Tops with the CMS detector at the LHC”, invited talk at the “Giving Physics a Boost” Conference at the Stanford Linear Accelerator Center, July 9, 2009.
21. N. Hadley, “CMS: The Good, the Bad, and the Ugly”, Colloquium at the Physics Department Brookhaven National Lab June 2, 2009.
22. N. Hadley, “The Large Hadron Collider and the CMS Detector: A Voyage to Study Nature in the Moments just after the Big Bang and How Engineering Makes the Trip Possible”, invited lecture (“First Year Lecture”) to the incoming Engineering Students at Virginia Tech, August 26, 2010.
23. N. Hadley, “The Large Hadron Collider and the CMS Detector: A Voyage to Study Nature in the Moments just after the Big Bang”, invited public lecture at Maryland Day at the University of Maryland, April 28, 2012.
24. S. Eno, “Searching for New Particles at the LHC”, invited Colloquium at Boston University, Feb. 10, 2009.

25. S. Eno, “LHC Status and SUSY Search Preparations”, invited talk at the “Shedding Light on Dark Matter” conference, U. Maryland, Apr. 2, 2009.
26. S. Eno, “Road to Discovery”, three invited lectures at the joint CERN/FNAL Hadron Collider Physics school, CERN, June 2009
27. S. Eno, “New Results from D0 on the W width, charge asymmetry and on gauge couplings”, invited “Wine and Cheese” talk at FNAL, Sept. 4, 2009.
28. S. Eno, “Searches for Exotic Particles with the CMS Detector”, invited Seminar at the University of Pennsylvania, Sept. 29, 2009.
29. S. Eno, “The Standard Model at the Tevatron”, Four invited lectures at Tata Institute, Mumbia India, Dec. 2009.
30. S. Eno, “The Startup of the Large Hadron Collider”, Colloquium at Tata Institute, Dec. 2009.
31. S. Eno, “Physics with CMS - the Next Two Years”, CMS January School lecture, FNAL, Jan. 5, 2010
32. S. Eno, “ The Startup of the Large Hadron Collider”, Colloquium at FNAL, Jan. 6, 2010
33. S. Eno, “The Startup of the Large Hadron Collider”, Colloquium, U. Maryland, Jan. 19, 2010
34. S. Eno, “The Startup of the Large Hadron Collider”, Colloquium, Rutgers, Feb. 3, 2010
35. S. Eno, “Missing-Transverse-Energy-Based Searches at Colliders: ”Gateway to Dark Matter in the Laboratory”, APS April meeting, invited plenary talk, Washington, D.C., Feb. 15, 2010
36. S. Eno, “Report of the HEPAP Informal Working Group on the HEP University Program”, “Town Hall Meeting, APS DPF”, Washington, D.C., Feb. 16, 2010
37. S. Eno, “CMS Results from the 2009-2010 Running”, Colloquium, SLAC, California, Apr. 6, 2010
38. S. Eno, “Status of (Undergraduate Research at) the Large Hadron Collider”, Invited talk, Gordon Conference, Mount Holyoke, MA, Jun. 9, 2010
39. S. Eno, “The LHC: Results from the Energy Frontier”, Colloquium, Texas A&M, Sep. 30, 2010
40. S. Eno, “SUSY Results from CMS”, invited talk, LHC at BNL Workshop, Brookhaven National Lab, Jan. 10, 2011
41. S. Eno, “The LHC: Results from the Energy Frontier”, invited Colloquium, Goddard Space Flight Center, Jan. 21, 2011
42. S. Eno, “The LHC: Results from the Energy Frontier”, invited Colloquium, APS Mid-Atlantic Senior Physicists group, Apr. 19, 2011
43. T. Kolberg, “Photon production at ATLAS and CMS” invited talk at the 24th Rencontres de Blois, Particle Physics and Cosmology, Blois France, May 30, 2012.

A.2 CMS notes co-authored by members of the Maryland Group

1. CMS AN-2011/297 "Studies of Pileup Effects on Missing ET Reconstruction" S. Eno (and others)
2. CMS-2010/361 "Search for Pair Production of First-Generation Scalar Leptoquarks Using Events Produced in pp Collisions at $\sqrt{s} = 7TeV$ containing one electron, two jets, and large missing transverse energy" S. Eno, D. Ferencek, P. Rumerio, F. Santanastasio, E. (Lockner) Twedt
3. CMS AN-2010/230 "Search for Pair Production of First Generation Scalar Leptoquarks Using Events containing two electrons and two jets produced in pp collisions at $\sqrt{s}$ =7 TeV" S. Eno, D. Ferencek, P. Rumerio, F. Santanastasio, E. (Lockner) Twedt
4. CMS AN-2010/071 "Data Flow for the CMS Exotica Group for Early Running" S. Eno, K. Rossato, P. Rumerio, E. (Lockner) Twedt (and others)
5. CMS AN-2009/055 "Searching for Stopped Gluinos during beam-off perios at CMS" S. Eno, K. Rossato, A. Skuja (and others)
6. CMS AN-2010/219 "Results of a visual scan of high MET events in 7 TeV pp colision data" D. Ferencek, F. Santanastasio (and others)
7. CMS DN-2010/008 "Optimization and Performance of HF PMT Hit cleaning algorithms developed using pp collision data at $\sqrt{s} = 0.9$, 2.36, and 7 TeV D. Ferencek, F. Santanastasio, J. Temple (and others)
8. CMS AN-2010/029 "Commissioning of Uncorrected Calorimeter Missing Transverse Energy in zero bias and minimum bias events at $\sqrt{s} = 900$ and 2360 GeV S. Eno, D. Ferencek, F. Santanastasio (and others)
9. CMS AN-2010/007 "JetMET Data Quality MOnitoring and prompt analysis of jets in the first collision data at cms" F. Santanastasio, D. Ferencek (and others)
10. CMS An-1009/035 "Offset Energy Correction for Cone Jets" S. Eno, D. Ferencek (and others)
11. CMS AN-2001/492 "Search for first generation scalar leptoquarks in pp collisions at $\sqrt{s} = 7$ TeV P. Rumerio, F. Santanastasio (and others)
12. CMS CR-2001/044 "Search for pair production of leptoquarks in the CMS Experiemtn" P. Rumerio
13. CMS CR-2010/189 "Searches for non-SUSY particles decaying to leptons with the CMS detector". P. Rumerio
14. CMS CR-2011/071 "Exotica Searches at the CMS Experiment" F. Santanastasio
15. CMS CR-2010/097 "Searches with early data at CMS" F. Santanastasio
16. CMS CR-2009/173 "Prospects for Exotica searches at ATLAS and CMS Experiments" F. Santanastasio

17. CMS AN-2012/002 "Search for Stopped Particles produced in pp collisions at $\sqrt{s} = 7$ TeV with 3.84 fb^{-1} at CMS A. Skuja, J. Temple (and others)

18. CMS AN-2011/181 "Search for Stopped Particles produced in pp collisions at $\sqrt{s} = 7$ TeV at CMS A. Skuja, J. Temple (and others)

19. CMS AN-2010/337 "ttbar cross-section in the muon+jets channel with muons-in-jet" J. Temple (and others)

20. CMS AN-2010/330 "Optimization and commissioning of jet substrcture algorithms" N. Hadley, M. Kirn, J. Temple

21. CMS IN-2010/020 "Abort Gap operations for CMS HCAL" J. Temple (and others)

22. CMS AN-2010/184 "First Results of the Search for Stopped gluinos in pp collisions at $\sqrt{s} =$ 7 TeV at CMS. S. Eno, K. Rossato, A. Skuja, J. Temple (and others)

23. CMS AN-2010/173 "Selection of ttbar candidates in the muon+jets channel" N. Hadley, M. Kirn, J. Temple (and others)

24. CMS AN-2010/145 "Measurement of the ttbar production cross section in the muon+jets channel using b tagging and a multivariate analysis technique" N. Hadley, M. Kirn, J. Temple

25. CMS AN-2010/080 "Studies of top tagging algorithms" N. Hadley, M. Kirn, J. Temple (and others)

26. CMS AN-2009/095 "Search for resonances close to top-pair production in the muon channel" N. Hadley, M. Kirn, J. Temple (and others)

27. CMS AN-2009/086 "Search for TeV top resonsnaces into jets plus mon" N. Hadley, M. Kirn, J. Temple (and others)

28. CMS IN-2009/001 "Measurement of HO HPD nosie rates during October 2008 re-commissioning of the CMS magnet at 3.8 Tesla and experience of operation of HO HPDs during CRAFT" K. Rossato, J. Temple, A. Skuja, D. Kellogg, E. Lockner (and others)

29. CMS DN-2011/003 "high-speed imaging photo-detection systems A. Baden, R. Bard (and others)

Appendix B

Curricula Vitae, Collaborators and Advisees

B.1 Collaborators and Graduate Student and Postdoctoral Advisees

During the past five years, Professors Baden, Eno, Hadley, and Skuja have been members of the CMS collaboration. They have worked most closely with the members of the Hadron Calorimeter group in CMS. Professors Eno and Hadley have also been members of the DØ collaboration in that time period. Professors Jawahery and Roberts have been members of the Babar and SuperB experiments. They have recently joined the LHCb experiment.

Our postdoctoral and graduate student advisees are listed in the beginning of the narrative sections for both our Energy Frontier and Intensity Frontier activities.

The publications to which we have made significant contributions are described and listed the narrative sections. The CMS Internal Notes on which we are co-authors are listed in Appendix A along with talks by all members of our group.

B.2 CVs

The CVs for the senior researchers are given on the pages that follow.

Andrew R. Baden
Professor

Education:

B.A. (History)	Univ. of Wisconsin at Madison	1975
B.A. (Physics)	San Francisco State Univ.	1981
Ph.D.	Univ. of California (Berkeley)	1986

Experience in Higher Education:

2006 -	Chair, Physics Department, University of Maryland
2004 -	Professor, University of Maryland
1995-2004	Associate Professor, University of Maryland
1990-95	Assistant Professor, University of Maryland
1989-90	Assistant Research Scientist, University of Maryland
1986-1989	Research Associate, Harvard Univrsity

Honors and Awards:

U. C. Berkeley Faculty Association for Teaching Excellence - 1982
SSC Fellow - 1991-1992
APS Fellow (Division of Particles and Fields) - 2004
Member Board of Directors Fermi Research Alliance - 2008

Sarah Catherine Eno

RESEARCH FIELD

Experimental High Energy Physics

PROFESSIONAL POSITIONS

University of Maryland

July 2005 to present: Professor of Physics

July 1999 to 2005: Associate Professor of Physics

Aug. 1993 to June 1999: Assistant Professor of Physics

University of Chicago

Oct. 1992 to Aug. 1993: Research Scientist

Oct. 1989 to Oct. 1992: Research Associate

EDUCATION

University of Rochester

1990: Ph.D., Physics

1986: M.A., Physics

Gettysburg College

1984: B.A. Physics, Summa Cum Laude, and minor in mathematics

HONORS

Fellow of the American Physical Society 2009

US DOE High Energy Physics Advisory Panel (HEPAP) 2007 - 2010

Fermilab Physics Advisory Committee 2005 - 2009

Executive Committee - Division of Particle and Fields of APS 2004 - 2007

DOE Outstanding Junior Investigator Grant 1994

Rush Rhees Fellowship, Univ. of Rochester, Sept. 1985 - June 1987

Salutatorian, Gettysburg College, 1984

Phi Beta Kappa, junior standing, Gettysburg College

Nicholas John Hadley

Employment

1995–Present	Professor of Physics University of Maryland.
2007–2010	Associate Chair for Undergraduate Education, Physics Dept., University of Maryland.
1988–1995	Associate Professor of Physics University of Maryland.
1988	Associate Professor of Physics Yale University .
1984–1988	Assistant Professor of Physics Yale University.
1983–1984	Associate Research Physicist Yale University.

Education

University of California at Berkeley	Ph.D in Physics June 1983. M.A. in Physics June 1978.
Yale University	B.S. May 1976. Graduated Phi Beta Kappa, summa cum laude, with distinction in physics.

Honors and Awards

Vice Chair - Division of Particles and Fields of the American Physical Society (APS) 2013.
Elected Fellow of the American Association for the Advancement of Science 2008.
Cornell Physics Advisory Committee 1998-2003, 2005
Secretary-Treasurer - Division of Particle and Fields of the APS 2001–2003.
Elected Fellow of the American Physical Society 1997.
Executive Committee - Division of Particle and Fields of the APS 1997–2000.
Fermilab Physics Advisory Committee 1997–2001.
Brookhaven High Energy and Nuclear Physics Program Advisory Committee 1996–1999.
Chairman Fermilab Users Executive Committee 1994–1995.
NSF Presidential Young Investigator Award 1988–1993.
U. of Maryland Graduate Research Board Semester Research Award 1991–1992, 1998-1999
DOE Outstanding Junior Investigator Grant 1988.
John H. Wheeler and Elliot H. Wheeler Fellowship 1976–1977.
DeForest Pioneers Prize 1976.

CURRICULUM VITAE– Abolhassan Jawahery

Education:

Ph.D.	Tufts University	June 1981 Physics
M.S.	Tufts University	December 1977 Physics
B.S.	Tehran University, Iran	June 1976 Physics

Employment Background:

Distinguished University Professor, Univ. of Maryland	2012-present
Gus T. Zorn Professor, Dept of Physics, Univ. of Maryland	2005-present
Professor,Dept. of Physics, Univ. of Maryland	1998-present
Associate Professor, Dept. of Physics, Univ. of Maryland	1992-1998
Assistant Professor, Dept. of Physics, Univ. of Maryland	1987-1992
Research Assistant Professor, Syracuse University	1986-1987
Research Associate, Syracuse University	1981-1986

Visiting Scientist

Cornell Electron Storage Ring (CESR), Cornell Univ. 1981-1987
CERN Laboratory, Geneva, Switzerland 1990
Stanford Linear Accelerator Center (SLAC) 2001-2002
Stanford Linear Accelerator Center (SLAC) 2006-2008

Honors and Awards

Elected Fellow of the American Association for the Advancement of Science (AAAS) (2010)
Elected Fellow of the American Physical Society (APS) (2004)
Distinguished Faculty Graduate Research Board award (2001)
UMD Graduate Research Board Semester award (2000)
UMD Graduate Research Board Research support award (1988)
Rapporteur speaker at the Lepton-Photon Symposium (2003)
Conference summary speaker at the conference on Flavor Physics and CP Violation (2006).
Conference summary speaker at the XLIVth Rencontres de Moriond conference on Electroweak Interactions and Unified Theories (2009).
Conference summary speaker at the conference on Flavor Physics and CP Violation (2010).

Professional Activities

Spokesperson, BaBar Experiment, Stanford Linear Accelerator Center (SLAC), 2006-2008.
Associate Editor, Annual Review of Nuclear and Particle Science, 2003-present
Physics Analysis Coordinator, BaBar experiment, SLAC, 2001-2002.
Physics Analysis Coordinator, CLEO experiment, Cornell Electron Storage Ring, 1987-88.
Member, Particle Data Group (PDG) collaboration, 2002-2005

Name: Richard G. Kellogg
Title: Senior Research Scientist

Education:

B.A.	Amherst College	1970
Ph.D.	Yale University	1975

Employment:

1975-78	Research Associate, Yale University
1978-82	Research Associate, University of Maryland
1982-88	Asst. Research Scientist, University of Maryland
1988-93	Assoc. Research Scientist, University of Maryland
1993	Senior Research Scientist, University of Maryland

IV. **Honors and Awards**

Graduated magna cum laude, B.A. Amherst College 1970.

Douglas Alan Roberts

Employment

2004–Present	Associate Professor of Physics University of Maryland.
1998–2004	Assistant Professor of Physics University of Maryland.
1996–1998	Assistant Research Physicst University of California at Santa Barbara.
1994–1996	Postdoctoral Research Fellow University of California at Santa Barbara.
1989–1994	Research Assistant University of California at Los Angeles.
1988–1989	Teaching Assistant University of California at Los Angeles.

Education

University of California Los Angeles	Ph.D in Physics June 1994.
California Institute of Technology	B.S. May 1988 with Honors in Physics

Andris Skuja

Professor

Education:

B.A.Sc.	University of Toronto	June 1966
Ph.D.	Univ. of Calif. (Berkeley)	March 1972

Experience in Higher Education:

9/71-8/76	University of Oxford (UK)	Research Officer
8/76-7/81	University of Maryland	Assistant Professor
1/81-7/81	McGill University	Visiting Professor
7/81-7/89	University of Maryland	Associate Professor
1/83-12/83	DESY	Visiting Research Scientist
7/89 - present	University of Maryland	Professor
1/92-7/92	SSCL	Guest Scientist
1/93-7/93	SSCL	Guest Scientist

Honors and Awards:

APS Fellow (DPF)
Maryland GRB Semester Research Award (1991)

Professional Activities:

American Physical Society
Canadian National Science and Engineering Research Council,
Grant Selection Board (1986-88)
Referee for DOE and NSF contracts and grants
Referee for Physical Review and Physical Review Letters