UPR/Mayaguez High Energy Physics

Final Report
to the
Department of Energy
Office of Science
Office of High Energy Physics

University of Puerto Rico
Mayaguez, Puerto Rico
Principal Investigator : Angel M. Lopez
angel@charma.uprm.edu, 787-265-3844

Report Period : June 1, 1997 - July 31, 2013

Grant Number : DE-FG-02-97ER41045

Contents

1 Abstract

For the period of sixteen years covered by this report (June 1, 1997 - July 31, 2013) the High Energy Physics Group at the University of Puerto Rico's Mayaguez Campus (UPRM) carried out an extensive research program that included major experiments at Fermi National Accelerator Laboratory (Fermilab), the Cornell Electron-positron Collider and CERN. In particular, these were E831 (FOCUS) at Fermilab, CLEOc at Cornell and the Compact Muon Solenoid (CMS) at the Large Hadron Collider (LHC) at CERN.

The group's history is one of successful execution and growth. Beginning with one faculty researcher in 1985, it eventually included four faculty researchers, one post-doctoral research associate, two undergraduates and as many as six graduate students at one time working on one of the experiments that discovered the Higgs boson. Some of this expansion was due to the group's leveraging of funds from the Department of Energy's core grant to attract funds from National Science Foundation programs not targeted to high energy physics. Besides the group's research productivity, its other major contribution was the training of a large number of MS students who later went on to successful technical careers in industry as well as academia including many who obtained PhD degrees at US universities.

In an attempt to document this history, this final report gives a general description of the Group's work prior to June 1, 2010, the starting date for the last grant renewal period. Much more detail can, of course, be found in the annual reports submitted up to that date. The work during the last grant period is discussed in detail in a separate section.

To summarize the group's scientific accomplishments, one can point to the results of the experiments. Both FOCUS and CLEOc were designed to carry out precise measurements of processes involving the heavy quarks, charm and bottom. Heavy quarks are particularly interesting because, due to their mass, theoretical calculations based on the Standard Model have less uncertainty than those for the light quarks. Precise heavy quark experiments can therefore yield some of the best tests of the Standard Model and of the approximations that are made in calculating measurable observables. Both FOCUS and CLEOc were highly successful achieving significant improvement in the precision of measurements such as lifetimes and decay branching ratios. For example, FOCUS obtained a data sample that contained ten times as many heavy quark decay events as its predecessor.

CMS was a big shift in the group's research. During the first decade of the century it became clear that the LHC would be the world's highest energy accelerator offering a unique opportunity for discovery. Given the UPRM's group record of achievement, it was successful in obtaining admission to the CMS collaboration in March, 2006, becoming the first institution to do so that did not have a PhD program. CMS is one of two major experiments at the LHC. Although the plans are for these experiments to run for many years with increased energy and event rates, they have already achieved one of their principal goals. The test for the existence of the Higgs boson, a particle which plays a unique role in the Standard Model but had not been observed, was answered in the affirmative in 2012.

The particular contributions of the UPRM group to these experiments make up the majority of this report although other contributions such as the training of students, outreach to the general community and the organization of scientific meetings are also discussed.

2 Project Summary, 1997-2010

The unifying topic of most of the group's work during this period was heavy-quark physics in a fixed-target charm experiment at Fermilab (FOCUS), in the detailed preparations for a Fermilab collider experiment to study CP violation in the B sector (BTeV) and in the work on CLEOc at Cornell. UPRM began to shift its attention to the CMS experiment at the LHC in 2005 and the speed of this shift was accelerated after it was accepted as a CMS member institution in March, 2006. A related research activity from the beginning was the development of improved statistical techniques to be used in the analysis of data from these experiments.

2.1 Personnel, 1997-2010

At the beginning of the grant period there were only two faculty members in the UPRM High Energy Physics Group; they worked on this project until 2013. Angel Lopez from the Physics Department was the Group Leader throughout the grant period and Wolfgang Rolke from the Mathematics Department was his collaborator on projects related to methods of statistical analysis. Dr. Lopez was named by the Secretary of the Department of Energy to the High Energy Physics Advisory Panel (HEPAP) from 2000-2003. Dr. Hector Mendez joined the Group in 2000 as a junior faculty member and so did Dr. Juan Eduardo Ramirez in 2003. Dr. Mendez and Dr. Ramirez worked on the project until 2013 also.

Several post-doctoral Research Associates worked on this project through the years. Until 2010 these were (in chronological order) Yangling Zhang, Weijun Xiong, J. Eduardo Ramirez, Zhongchao Li, Xingtao Huang, Surik Mehrabyan and Andriy Zatserklyaniy.

In terms of human resources, the largest impact of this project was in the number of Puerto Rican and Latin American students that received Physics MS degrees fulfilling their thesis requirement with research projects that were important contributions to our experiments. As can be seen from Table 1, many went on to finish PhD degrees at prestigious universities but all have gone on to successful careers using the training they received in computing and electronics. All of them had the opportunity to spend time at world-class high energy physics laboratories, an experience which was life-changing in many cases. For the Latin American students in particular, this experience forced them to improve their English language skills which opened up many opportunities.

This research project also had an important impact on the undergraduate students in the Physics Department at UPRM. Since the project began until 2010, thirty-eight UPRM undergraduates participated in summer internships at Fermilab under the auspices of a variety of programs while there had been none before then.

Name	MS Year	Higher Degree or Current Position
Luis Mendez	1996	Univ. Prof., Dominican Republic
David Olaya	1997	PhD in Physics, U of Colorado
Eduardo Ramirez	1997	PhD in Physics, U of Colorado
Enrique Montiel	1997	Univ. Prof., Mexico
Alejandro Mirles	1998	Univ. Prof., Puerto Rico
Carlos Rivera	1998	Research Group Leader, Raytheon Corp
Hugo Hernandez	2002	IT Professional, USA
Eduardo Luiggi	2003	PhD in Physics, Vanderbilt
Alexis Paris	2003	Industrial Research, Puerto Rico
Mauricio Penagos	2003	Univ. Prof., Colombia
Jose Quinones	2006	Univ. Prof., Puerto Rico
Osvaldo Aquines	2006	PhD in Physics, Germany
Carlos Florez	2007	PhD in Physics, Vanderbilt
Arjuna Castrillon	2007	Univ. Prof., Colombia
Miguel Bonnett	2008	Univ. Prof., Peru
Neida Santacruz	2008	PhD in Education, UPR
Iveth Mendoza	2009	Univ. Prof., Colombia

Table 1: MS Graduates before 2010

2.2 FOCUS Experiment

The UPRM group's first experiment at Fermilab was actually E687, a charm photoproduction experiment which ran in 1988-91 and produced over 40 refereed publications. E687's follow-on experiment was FOCUS (an acronym for FOtoproduction of Charm with an Upgraded Spectrometer) which ran in 1996-97 with the ambitious goal of a tenfold increase in E687's statistics and a concurrent reduction in background. That goal was achieved. FOCUS (also known as E831) reconstructed more than 1,000,000 charm events and published 55 peer reviewed papers.

In FOCUS, the UPR responsibilities included four major systems: one of the muon detector stations, the muon trigger and two Cerenkov counters. All four systems were ready on time for the start of the run in July 1996. Our interest in muon physics led us to undertake the design and implementation of a first-level inner muon trigger and the refurbishing of the existing muon trigger counters. The recommissioning of two Cerenkov counters (C2 and C3) were major projects as was the development of a new algorithm for muon identification which minimized misidentification of pions as muons. Contributions were made to the simulation of the inner muon system in FOCUS as well as to the development of routines related to the adjustment/calibration of the FOCUS muon and Cerenkov detectors. The group's contributions also included monitoring of data acquisition and participation in the primary and secondary data reduction as well as the development of simulation, data acquisition and analysis software. The UPRM was solely responsible for the secondary skim of one of the main portions of the FOCUS data set, the leptonic stream.

In terms of the specific physics data analyses to which UPRM contributed, two main lines can be mentioned. One is the group of analyses that relied on decays to final states containing a muon. Dr. Ramirez played a major role in the development of the FOCUS inner muon identification software package as part of his M.S. thesis research at Mayaguez and this algorithm was a basic element of any analysis of decays to muons.

The other line of analyses was that of hyperon decays. This was a continuation of work started by Dr. Ramirez while he was a PhD student at the University of Colorado. There he worked on improvements to a hyperon (Ξ^-, Ω^-) reconstruction algorithm, which reduced the background, while keeping nearly 100% efficiency. After Colorado, Dr. Ramirez took a Research Associate position at UPR/RUM in August, 2002, where he continued this line of research. He was one of the lead authors of a FOCUS publication on the measurement of several Ξ_c^+ branching ratios and, after becoming an Assistant Professor at UPRM, another publication searching for exotic particles known as pentaquarks which some experiments had claimed to have discovered. He searched for the decay channel $\Xi_5^{--} \rightarrow \Xi^-\pi^-$, and set an upper limit in a mass region from 1.480 GeV/c^2 to 2.400 GeV/c^2 using as the normalization channel the decay $\Xi^*(1530)^0 \rightarrow \Xi^-\pi^+$. A list of the publications to which group members made major contributions can be found in Section 4.

2.3 BTeV

BTeV's main goal was the study of CP violation in the B sector where its effects are large. The collaboration proposed a complete program of precise measurements in order to understand the effect fully. In addition, BTeV would have carried out high-statistics studies of charm and B decays and searches for forbidden and rare decays. Unfortunately, after much detailed design, BTeV was eliminated from the US HEP program. Nonetheless, it constituted one of the UPRM group's main activities for several years.

BTeV expected to reconstruct more than 10^8 B decays per year. A great deal of work was done by the collaboration to design the most appropriate spectrometer. This work is documented in the Technical Design Report. Physics simulations were carried out using both MCFast (a Monte Carlo package developed by the Fermilab Computing Division for fast and flexible detector design studies) and GEANT. MCFast was used to determine the general characteristics of the baseline detector elements. GEANT simulation was used to do a more detailed design which was the basis for a detailed and realistic construction budget.

The UPR carried out the bulk of the development of the GEANT simulation of the BTeV muon detector and contributed significantly to the development of dimuon trigger algorithms. We also collaborated in the construction of prototype muon detector units and in their beam tests at Fermilab.

2.4 CLEOc

CLEOc was a dedicated program of charm physics at the Cornell Electron Storage Ring (CESR) $\mathbf{e^+e^-}$ collider located at the Laboratory for Elementary Particles Physics (LEPP) at Cornell University at Ithaca, New York. The experiment was designed to make very high precision measurements of charmed mesons ($\mathbf{D^0}$, $\mathbf{D^+}$, $\mathbf{D^-}$ and $\mathbf{D_s^\pm}$) and to test quantum chromodynamics (QCD), which included a complete set of measurements for hadronic, leptonic and semileptonic charm decays, detailed studies on the lowest and highest mass charmonium states and searches for evidence of new physics beyond the Standard Model by searching for rare D and τ decays, $\mathbf{D\overline{D}}$ mixing and CP violating decays. The experiment accumulated a data set of approximately 750 pb^{-1} at the $\psi(\mathbf{3770})$ energy and 750 pb^{-1} at the 4170 MeV energy. It also obtained $\sim$30 million $\psi(2S)$ decays for charmonium physics.

The University of Puerto Rico joined CLEOc in November of 2003. Our Research Associate was located permanently at Cornell working on the data acquisition process (service task) and on physics analysis. Dr. Zhongchao Li was resident at Cornell since the group joined the collaboration. He developed and set up all the tools needed to do the service work that was our responsibility. Dr. Mehrabyan joined the group after the departure of Dr. Li and remained at Cornell during the period of data acquisition. Dr. Mendez, with graduate students, spent full-time at Cornell during two consecutive summers (2004-2005) working on CLEOc data analysis.

Besides taking shifts during the data acquisition period, our service work consisted of:

- Tuning of the Inner Drift Chamber (ZD) Monte Carlo
- Testing the CLEO software releases
- Testing the quality of generated Monte Carlo samples

The group was actively involved on physics projects as well as service work at the experiment.

The physics topics studied were:

- R Measurement at CLEO,
- Search for $\chi_c \to VV$,
- $J/\psi \to \pi^+\pi^-\pi^0 K^+K^-$,
- Br($\mathbf{D^0} \to K^-\pi^+\gamma$),

Results from these studies were presented at CLEO collaboration meetings and at two international conferences. Dr. Mehrabyan presented “R CLEO Measurements” at the Quarkonium Group Workshop (QGW, June 2006) and Dr. Mendez presented “CLEOc Recent Results” at the Latin American Symposium on High Energy Physics (SILAFAE, November 2006).

2.5 CMS

CMS is one of two major experiments at the LHC. A multi-purpose spectrometer designed to run with high luminosity at the energy frontier [1], its main goals are to study the mechanism of electroweak symmetry breaking and to search for possible new physics phenomena which are more speculative but which could have an even greater impact on our understanding of fundamental physics. In the latter one would include the search for supersymmetry and for extra dimensions. CMS also carries out precision studies of known physics. Such studies can give indications of physics beyond the SM and complements the direct searches.

Since the UPRM group wanted to maximize its impact on CMS and since most of the CMS subdetectors were already built when the group was admitted, it chose to work with a subdetector that was yet to be installed, the forward pixel system. From September 2005 until June 2007, the UPR group carried out a large number of projects in CMS both in software as well as in hardware. During this period the group was stationed at Fermilab. Here is a list of the software projects:

(1) Definition of the forward pixel geometry in the (then) new CMSSW software framework. (2) Implementation of code to take into account (in both simulation and reconstruction) the $\vec{E}\cdot\vec{B}$ effect on electron drift in the pixels. (3) Comparison of pixel simulation and beam test data which led to adjustment of simulation parameters and demonstrated the importance of simulating delta ray production. (4) Validation of the electromagnetic calorimeter simulation.

These projects were carried out under the sole responsibility of UPRM.

The hardware projects were: (1) Beam test of CMS pixel modules at the Meson Test Facility. (2) Installation of a stand for system tests of a section of the forward pixels. (3) Testing of the production pixel plaquettes before installation into the detector. (4) Characterization and testing of the forward pixel power supplies and cables.

All but project (4) were collaborations with other CMS institutions. The analysis of the data from the beam test was published in NIMA on March 1, 2009 [2].

During the summer of 2007 the focus of work on the CMS forward pixel detector started to shift from Fermilab to CERN where test stands were set up at the Tracker Integration Facility (TIF) in preparation for installing a partial detector for the start of LHC operations which were scheduled for that year. Our Research Associate spent several months at CERN in order to be able to work directy with the hardware under simulated run conditions. Due to the delay in LHC startup until 2008, the plan was changed and it was decided that the full pixel detector would be installed. In fact, it was installed in time to participate in the Cosmic Run at Full Tesla (CRAFT08) exercise.

UPRM carried out a number of important projects related to the CMS forward pixel detector. One which was under the sole responsibility of UPR involved the Detector Control System (DCS)that is used to monitor the operating conditions and to control the operation of the forward pixel detector. UPRM developed the software for a particular readout unit called the Detector Control Unit (DCU) which is used to handle the data from some of the temperature sensors and to monitor the power supply voltages. We built a test station at the Silicon Detector Facility (SiDet) at Fermilab. The SiDet data acquisition system was modified to provide readout of DCU temperature and a methodology was developed to calibrate the DCU temperature readings using a reference thermometer sensor. For the real detector, DCU readout had to be implemented as modules of the XDAQ data acquisition system which is the framework for data acquisition in CMS. During CMS data acquisition these modules are used to extract the DCU data from the regular data stream and to channel it to the DCS system where it is monitored. Other modules developed by UPRM allow the communication with the configuration database which holds the calibration parameters that need to be loaded at startup and the communication with the conditions database which keeps a permanent record of run conditions during the experiment. Other major pieces of software were developed to carry out the calibration procedure while the detector was at the Tracker Integration Facility. The end result of this project was a DCU data system which operates stably and provides important monitoring information during CMS data acquisition.

Another project related to the pixel system installed at CMS involved a detailed study of the calibration procedure that determines the parameters of the linear dependence between signal pulse height and signal charge. This project was carried out in collaboration with the the Paul Scherrer Institute (PSI) in Zurich, Switzerland. During the construction of the pixel detector, an absolute calibration had been performed for each of the pixel chips (each containing 4160 pixels) by submitting them to nuclear decay radiation sources of well defined energy. In this procedure data from all pixels in a given chip was analyzed as a single sample so that the resultant parameters reflected the collective behavior of 4160 pixels. In our study six chips were put through a rigorous test procedure which followed that of the actual production modules except that the nuclear source tests were much prolonged in order to gather sufficient statistics to analyze the data on a pixel by pixel basis. It was found that fluctuations in the pixel to pixel behavior among pixels in the same chip were larger than fluctuations in the chip to chip comparison. Since it is not viable to do a pixel by pixel calibration for all the pixels in the detector, this study provided an important piece of information on the true pixel to pixel variation which needs to be considered in analyzing the pixel data.

The other UPRM CMS projects carried out before June, 2010, were related to R&D for an upgraded pixel system. Such an upgrade is necessary for the detector to handle the increases in LHC luminosity contemplated in the future. This was the motivation for two hardware projects: (1) a study of the performance of the existing CMS pixel sensor and readout chip (ROC) composite units which were irradiated to various fluences in test beams and (2) a study of the performance of a proposed alternative to the communication between the barrel pixel modules and the optical data hubs located outside the active volume of the pixel detector. Again these were done in collaboration with PSI.

The existing CMS pixels had been tested up to the fluence ($6x10^{14} n_{eq}/cm^2$) expected during the first few years of running at the design LHC luminosity. They had not been tested above these levels. For this project, individual units were irradiated with 26 GeV/c protons with a range of fluences up to $5x10^{15} n_{eq}/cm^2$. Other samples were irradiated with positive pions of 280 MeV/c momentum with fluences that varied up to $6x10^{14} n_{eq}/cm^2$. The response of the units to a Sr-90 source was investigated. In order to study how much the reduction in performance due to the radiation damage could be diminished by raising the bias voltage, the bias voltage was scanned during the test runs with the maximum voltage applied being larger for the chips with the larger fluences. The results of this study indicated that the design of the existing CMS pixel sensors did not need major changes for use in a Phase I LHC upgrade. Increased bias voltage significantly improved the performance of irradiated chips. For example, a signal of 10000 electrons was observed for bias voltages in the 400 to 600V range for the chips that received $1.1x10^{15} n_{eq}/cm^2$.

The results of this project were presented by our graduate student at the 13th RD50 Workshop held at CERN in November 2008.

Another upgrade project concerned the need to minimize the material in the active tracking volume. In the existing pixel detector track reconstruction efficiency losses can be as high as 10% for pions at $\eta = 1.5$ due to nuclear interactions in the barrel pixel infrastructure (mechanical support, cooling and cabling). This project was a study of a proposal to replace the existing flat ribbon Kapton cables which carry electrical signals on parallel lines to and from the pixel modules with micro-twisted pair cables that would run directly from the modules to the optical links thus saving material in the cables themselves as well as eliminating the connection PC boards. To further reduce the amount of cabling it is also proposed to change the existing 40MHz analog parallel data link to a digital serial link running at 160 or 320MHz. Pixel modules were tested with the cable inserted in the data path and results compared to those obtained without the cable. It was found that, in order to obtain adequate performance with the micro-twisted pair cables, the termination resistance had to be adjusted to a different value for different cable lengths. With this adjustment, the dispersion in the signal is controlled and the power loss is less than 50% which is acceptable. These results were presented by our graduate student at the CMS Upgrade Workshop held at Fermilab in October 2009.

During this period the UPRM group began working on simulation of the upgraded CMS tracking system focusing on the effects of radiation damage. The goal was to make comparisons between different proposed geometries for the upgraded tracker. Another project studied the effects of a loss of tracker hit efficiency by sections on the overall tracking efficiency.

2.6 Statistical Analysis

By 1997 there had been major developments in the field of statistics that had yet to be applied to problems in the analysis of high energy physics data. The overall goal of this part of the UPRM research program was the development of analysis tools that would be useful to a variety of HEP experiments. The approach was to do this by attacking specific problems which arose in the physics analysis of the actual data from the UPR experiments. The direct collaboration between a statistician and the Mayaguez physicists ensured the excellent communication that is a prerequisite for the success of such an interdisciplinary enterprise.

The main focus of this research has been the development of the best statistical methods for setting limits and finding signals in situations where there are few data events. In particular methods were developed to set limits taking into account the uncertainty in the rate of background events and the more general case of the presence of other nuisance parameters such as the detection efficiency. The closely related problem of the optimum test for a new discovery was also studied. The basic strategy in this work was the use of the profile likelihood method in which the multi-dimensional likelihood function is reduced to a function that only depends on the parameter of prime interest. Detailed studies were carrried out that showed that the method has the correct coverage for the case of a signal with a Poisson distribution, a background with either a Poisson or a Gaussian distribution and an efficiency with either a Binomial or a Gaussian distribution. Later the method was generalized to the case that the signal is searched in several channels simultaneously.

A very important aspect of this work was the development of methods which were amenable to efficient calculation so that they could be used by physicists to search for signals in real data. In fact, efficient algorithms were developed and incorporated in the ROOT analysis software tool used by most high energy physicists.

By 2010 this collaboration had resulted in five publications in refereed journals including a FOCUS publication where several of these methods were used in the analysis of rare and forbidden 3-body dimuon decays of the charmed mesons D^+ and D_s^+. Three of the publications were in Nuclear Instruments and Methods. In addititon our statistician had been accepted as an associate member of the FOCUS, CLEOc and CMS collaborations and he had made several presentations at international conferences most importantly the PHYSTAT series of conferences held every two years.

2.7 Service Work

Members of the UPRM group also made contributions in benefit of the field of high energy physics in general as well as in educating the public on the work of high energy physicists.

Dr. Angel Lopez served as a member of the High Energy Physics Advisory Panel from 2000 to 2003. He was also a member of the International Advisory Committee for the series of Heavy Quark and Lepton (HQL) Conferences from 2003 until 2013 and President of the Local Organizing Committee for the HQL2004 Conference which was held in San Juan, Puerto Rico.

Dr. Hector Mendez is the Director of the UPRM QuarkNet Program which started in 2005 and continues to this day. This program holds frequent workshops attended by Puerto Rico high school physics teachers and eventually impacts thousands of students in Puerto Rico public schools.

3 Project Description, 2010-2013

Starting with the first collisions in November, 2009, the LHC accelerator performed better than expected and with increased energy and luminosity as the months went by. It reached a center of mass energy of 7 TeV on March 30, 2010, signaling the start of its main research program at the energy it would maintain until the end of 2011. After a short break, the LHC ran at an energy of 8 TeV during 2012 until it went into a prolonged shutdown a few weeks into 2013. Therefore the LHC was providing collisions to CMS during the majority of the last UPRM grant period.

By June 1, 2010, the UPRM group was completely dedicated to the CMS experiment. The CMS pixel detector which was our particular hardware project worked very well along with the other detectors in CMS. Our group participated by taking our share of data monitoring shifts at the CMS site at P5 and remote shifts at the LPC at Fermilab. A major accomplishment was the establishment of a Tier3 data analysis center at Mayaguez using supplemental equipment funds. The group also continued its projects on upgraded CMS detector development and on statistical analysis. Of course, the highlight during this period was the announcement of the discovery of the Higgs boson in July, 2012.

3.1 Personnel, 2010-2013

There were no changes in the faculty members during this grant period but Dr. Wolfgang Rolke was recognized by the CMS management by being named to the CMS Statistics Committee in April, 2011.

Our Research Associate, Dr. Andriy Zatserklyaniy left the group on June 30, 2011, to take a position as a Senior Research Associate at the University of California, Santa Cruz. His replacement, Dr. Eric Brownson joined our group on October 1. He received his PhD in HEP from the Univ. of Wisconsin in 2008 and already had extensive experience in CMS analysis and simulation. In fact, Dr. Brownson quickly became a Level-2 manager in the CMS upgrade simulation. Both Dr. Zatserklyaniy and Dr. Brownson were stationed at Fermilab during their tenure with our group.

Productivity in terms of MS students graduated was at a maximum during this grant period as can be seen from Table 2. This productivity was aided by the fact that basic funding from the DOE grant allowed us to obtain funding from the National Science Foundation that provided support for a total of four of these graduate students through its program, ”Partnerships in International Research and Education” (PIRE).

The PIRE grant also provided funds for a total of four Puerto Rican undergraduate students who spent summer internships at the Paul Scherrer Institute in Zurich, Switzerland. Of these four students, three are currently in PhD programs in the US.

Name	MS Year	Higher Degree or Current Position
John Acosta	**2010**	**PhD Candidate, U. of Mississippi**
Sandra Oliveros	**2010**	**PhD Candidate, U. of Mississippi**
Cesar Pollack	**2011**	**PhD Candidate, UPR**
Juan Cuevas	**2013**	**PhD Candidate, UMass**
Maria Falla	**2013**	**Univ. Prof., Colombia**
Joaquin Siado	**2013**	**PhD Candidate, U of Nebraska**
Soraya Flores	**2013**	**Univ. Prof., Peru**
Indira Vergara	**2013**	**Univ. Prof., Puerto Rico**

Table 2: MS Graduates since 2010

3.2 Equipment - CMS Tier3 Computing Center

Supplemental ARRA funds for equipment were provided to our group during this grant period and were available as of September, 2010. The funds were meant to improve our dedicated computing facilities in Mayaguez and to provide video-conferencing equipment. All the equipment acquired with ARRA funds was selected, purchased and delivered by May 31, 2011.

Our high energy physics computing cluster had been purchased from base grant funds but was quickly becoming obsolete and did not meet the requirements for a Tier3 computing center of the CMS computing structure. The design of our Tier3 was done in-house by Dr. Ramirez. A Dual Quad Core Xeon E5520 CPU 2.27 GHz, 5.86 GT/s Intel QPI with 24 GB of RAM 1066 MHz was selected for the head node. This node has a 160 GB internal hard disk drive. For the storage we connected a JBOD storage with 24 disk slots connected to an Adaptec raid controller (model 5085). Due to the limitation on the number of disks per RAID controller, it was necessary to use 2 RAIDs. One is a RAID level 6 with 9 disks of 2TB each for an effective total of $\sim$13 TB. The other is a RAID level 5 with 14 disks of 2TB each for an effective total of 22 TB. There is one disk as a global spare.

For the nodes we bought 20 servers, in which the base barebone is an Acmemicro 5036T-T. Each server has a single Quad core Xeon W3550 CPU (running 3.07 GHz, 4.80 GT/s Intel QPI), 12 GB RAM 1066 Mhz, one 2TB disk. Of these nodes 19 are the worker nodes, and one is the interactive node. A DELL PowerConnect 6248 switch is used for internal networking and the protection system consists of two UPS of 3000 VA for the nodes and switch and 2 UPS of 1500 VA for the headnode and storage JBOD.

After receiving the grid certicates, our cluster was configured as a CMS Tier3 as follows:

- 1 Computer Element (CE) or gatekeeper.
- 1 Storage Element (SE) or BestMan server.
- 1 Squid server for caching database.
- 19 working nodes (WN) for analysis.

- 1 interactive node (IN) for local users access.

To maximize our hardware for analysis, we configured a CE, SE and Squid server as virtual machines (VM). The VMs were installed in our head node. The head node had a total of 16 Single CPU cores,24 GB RAM and 30TB disk (our RAID). We split CPU, Memory and Disk as follows:

- 4 CPUs, 4 GB RAM, 60 GB local disk for CE.
- 4 CPUs, 4 GB RAM, 60 GB local disk for SE.
- 1 CPU, 2 GB RAM, 100 GB local disk for Squid server.
- 3 TB for home partion in head node
- 27 TB for data partion in head node

The ROCKS cluster software package and CONDOR were installed as well as the CMSSW software infrastructure which is particular to CMS. In addition, our Tier3 was registered with the Open Science Grid.

When the cluster began to be heavily utilized, we discovered there was a need to upgrade the memory of the head node and Cluster. The head node got 96GB RAM, which was split into 24GB for CE, 24 GB for SE with the capacity to increase as needed. The nodes got 24 GB RAM each (480 GB total).

After the upgrade our Tier3 was integrated into the CMS computing structure. In fact, some of the jobs for the computation of the CMS Higgs limits were analyzed successfully in our Tier 3.

Nevertheless, we noticed the cluster was not being used efficiently (only 50 % of capacity) during periods of high demand. The cluster was connected internally with only 1 Gb/s speed, so the maximum throughput from the RAID was limited by our own network. The first upgrade was to buy a 10Gb Ethernet card and an extra switch to connect the head node directly to the switch at 10 Gb. With the upgraded network we doubled our speed to about 2 Gb/s still far away from the hardware's limit. The problem was found to be the RAID software/hardware. We were at the maximum throughput that could be reached with a RAID structure, but when divided among 152 jobs (19 nodes each with 8 cores) it reduced the readout to 1.3-1.6 MB/s per job putting the CPU in a waiting state and reducing efficiency. To makes matters worse, this problem scales negatively as the cluster grows.

The problem of scalability was solved by implementing a distributed system called Hadoop and switching from RAID to Hadoop. In this new distributed system, the data is distributed and replicated among the cluster nodes in a way that it can grow with the cluster size and the network is shared uniformly for all nodes. Hadoop requires apart from the datanode two extra servers, a namenode that keeps track of the data location and a secondary node to make checkpoints of data. We began the implementation of Hadoop by setting a new Virtual Machine to act as namenode with 2 CPUs, 2GB RAM, 40GB disk, set our interactive node as secondary node, and used 1.5 TB (out of 2TB) from each node for a total of 30TB Hadoop space. To recover the disk capacity we had with the RAID system, we ordered 20 3TB disks for a total Hadoop capacity of 80 TB.

In the end our Tier3 cluster is recognized as a model configuration. In fact, we were asked to participate as a test institution in the migration of the grid tools from the current configuration using "Pacman" to the standard linux packaging "RPM" maintained by the Open Science Grid. The reason behind this transition is to facilitate future/current Tier3 centers in setting/upgrading their clusters. For this project, we upgraded Hadoop, SE, WN, IN, in collaboration with the Open Science Grid and with the steps being discussed in CMS Tier3 meetings.

For video conferencing we purchased a Polycom video conference system, including the audio system and 2 monitors. It allowed us to participate as a group in the experiment's meetings as well as in activities related to our QuarkNet high school physics teachers programs.

3.3 CMS Data Acquisition

The UPRM group fulfilled its responsibility of manning its share of data acquisition shifts during the entire LHC run. At the beginning of the run we participated in taking shifts at the CMS site at P5 monitoring the performance of the pixel system during data taking at increasingly high luminosity levels. Later this duty was carried out by taking offline Data Quality Monitoring (DQM) shifts at the Fermilab Remote Operations Center (ROC). This allowed us to perform CMS central shifts without the additional cost & burden of traveling to or being in Geneva, Switzerland. UPRM committed one senior person and one graduate student to officially perform its share of Offline DQM shifts. The Offline DQM shifter is responsible for validating the reconstruction and calibration of data taken by the CMS detector soon after it is taken. This shifter is required to create certified lists of good runs for use by all CMS physics analyses. The entire detector must be reviewed not just a single component. Taking shifts was a great teaching tool for graduate students just beginning their work on CMS.

3.4 CMS Upgraded Detector Development

During this grant period our group worked in collaboration with groups at Fermilab and at the Paul Scherrer Institute on projects related to the design of the CMS detectors to be used when the LHC is upgraded to run at higher luminosities. Some projects involved computer simulation of the radiation damage and the effects of the event pileup that will be observed at the higher luminosities. Others were involved with the hardware components directly.

3.4.1 Upgrade Simulations

To study the performance of CMS at the LHC we simulated a luminosity of $2 \times 10^{34}\ cm^{-2}s^{-1}$ which corresponds to adding an average of 50 PileUp, $\overline{\text{PU}} = 50$, events at 25 ns bunch spacing on top of the underlying physics events of interest. The additional particle multiplicity is expected to exceed the CMS design specifications.

The Pixel Tracking System at CMS is the closest detector to the interaction region and experiences a much higher particle flux than the other subdetectors. It is primarily responsible for reconstructing tracks and finding event vertices. The ability to reconstruct high quality vertices will only increase in importance as we move into higher and higher pileup regimes. The increased particle flux of the ever improving LHC will frequently overfill the buffers of the Read Out Chips (ROC) on the pixel detector. It will need to be replaced at the higher luminosity. The overriding design specification of the new pixel detector is that it should function at high luminosities $2 \times 10^{34}\ cm^{-2}s^{-1}$ with the same or better performance as the current pixel detector does at lower luminosities.

Other changes to the pixel system will be made besides the implementation of an improved ROC. A smaller diameter beam pipe will be installed that will allow for the innermost Pixel Barrel layer to be moved closer to the interaction point. Having more information closer to the interaction point will add the pixel systems vertexing ability. Vertexing will take an increasingly prominent role in analyses as we reach higher and higer amounts of pileup. The Upgraded detector will also be optimized to provide 4-pixel-hit coverage over the central η regions. A fourth barrel layer and a third pixel disk will be added to provide the 4-pixel-hit coverage. Even though more sensors will be installed the new pixel tracker will contain less mass due to a planned two-phase CO2 cooling scheme and light-weight mechanical supports. The electrical and cooling services will also be moved out radially and further down along the beam pipe thereby decreasing the material particles will interact with as they radiate out from the interaction point.

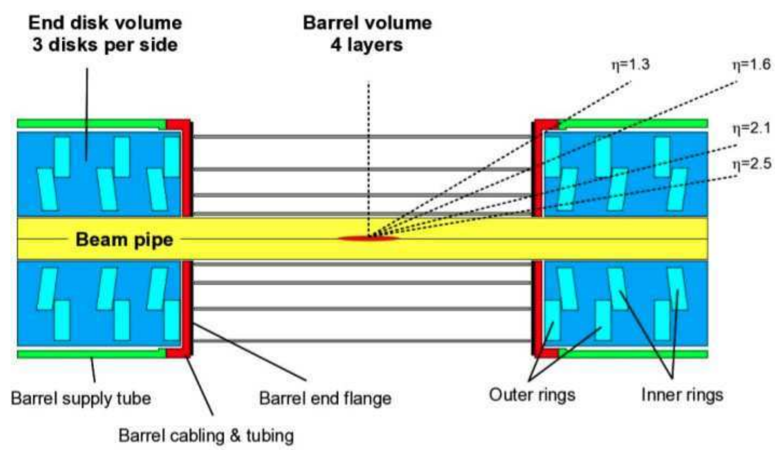

Figure 1: Conceptual layout for the Phase 1 upgrade pixel detector.

UPRM carried out a series of simulation studies comparing the performance of the current tracking system and the proposed upgraded tracking system for CMS. Some studies looked at the track finding efficiency & fake rate for tracks from $t\bar{t}$ events. These included simulations where several tracker modules were deactivated as they would be due to radiation damage. An example of one of the scenarios that was simulated is shown in Figure 2. The scenarios were selected on the basis of the probability of degradation. Figures 3 and 4 present the results for track finding efficiency & fake rate for the current and the upgraded tracker with and without degraded modules.

This is just one example of the many studies of this kind that the UPRM carried out in making a significant contribution to the design of the CMS upgrade. Another was a study to simulate radiation damage within the pixel system at the individual pixel level. The resulting tracking hit residuals were studied and propagated into the track finding. This was then compared to approximations of radiation damage achieved by raising pixel thresholds.

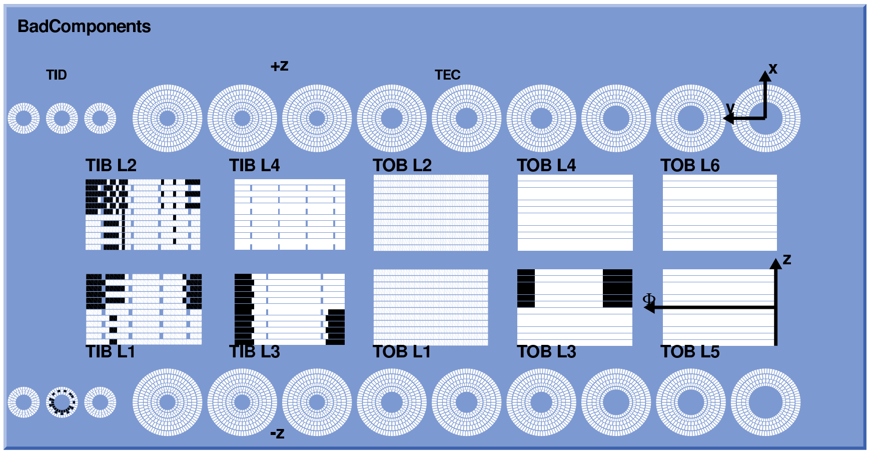

Figure 2: A CMS "Tracker Map" showing modules in black that are expected to degrade in performance in the future.

Major contributions were also made by UPRM to the computing infrastructure for the CMS upgrade simulations. Eric Brownson was one of two Offline Level-2 Coordinators for the Upgrade Project. In this role he was tasked with supporting & improving the simulations for the various proposed detector upgrades. Dr. Brownson maintained central web pages with detailed instructions for running the simulations of the various upgrade projects. He also played a central role in developing all of the workflows used for physics analyses with the upgraded detector components.

Dr. Brownson served as the release manager for the upgrade projects. This involved creating custom versions of CMS's software (CMSSW) package for the different upgrade projects. Before code was included in the custom CMSSW releases it was checked into the central Concurrent Versions System (CVS) repository & properly tested. Then Dr. Brownson was responsible for defining, compiling, testing & distributing the CMSSW RPMs. During the project period about 12% of all CMSSW releases installed on Fermilab's Tier 1 were created for the Upgrade project by Dr. Brownson.

As part of his duties as the release manager Dr. Brownson performed many small studies on demand. One representative example was looking into the particle multiplicity within the Minimum Bias MC that is used for the pileup sample. There are several tunes of Pythia that get used within CMS. At $\overline{\text{PU}} = 50$ any small differences between the tunes gets magnified fifty fold. In Figure 5 the number of generator level particles can be seen for four of the different tunes used at CMS. Studies such as this were used to explain many of the differences seen in the resulting physics analyses.

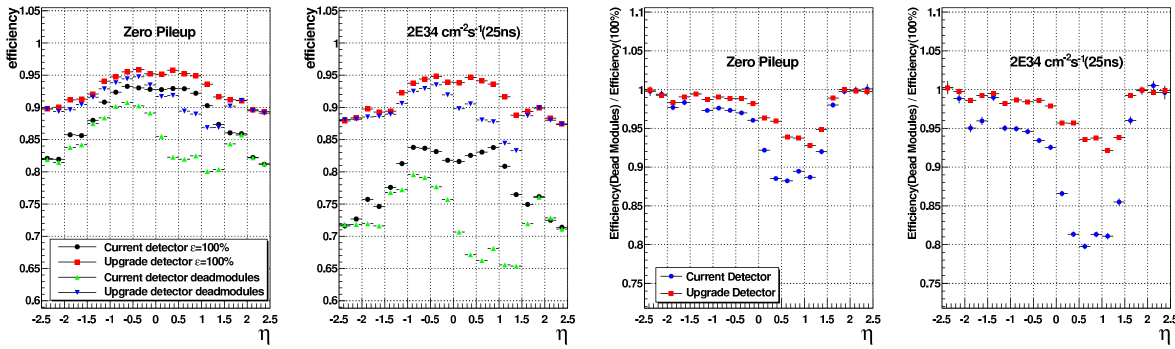

Figure 3: Tracking efficiency as a function of η for default tracks in a $t\bar{t}$ sample with (left) zero pileup, and (middle-left) an average pileup of 50. Results are shown for the current detector (black circles, green triangles), and the upgrade detector (red squares, blue inverted triangles); with Tracker modules at 100% efficiency (black circles, red squares), and with dead Tracker modules as explained in the text (green triangles, blue inverted triangles). Ratio of the tracking efficiencies with dead Tracker modules to the tracking efficiency with Tracker modules at 100% efficiency as a function of η for default tracks in a $t\bar{t}$ sample with (middle-right) zero pileup, and (right) an average pileup of 50. Results are shown for the current detector (blue circles), and the upgrade detector (red squares).

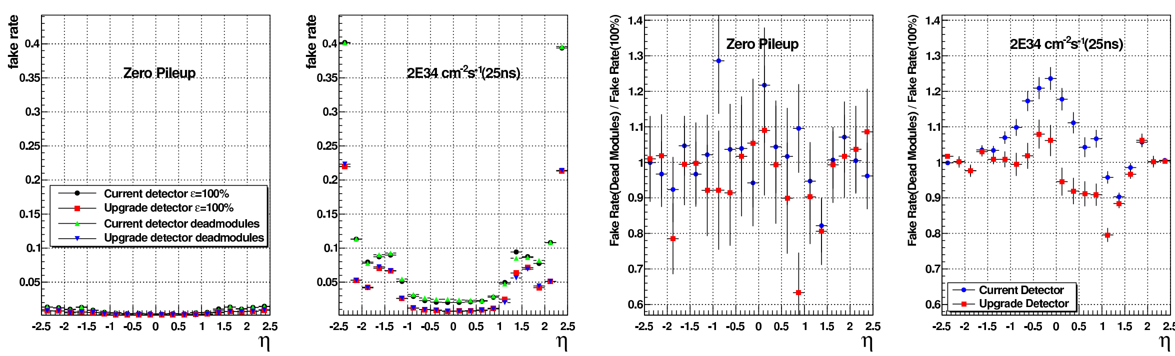

Figure 4: Track fake rate as a function of η for default tracks in a $t\bar{t}$ sample with (left) zero pileup, and (middle-left) an average pileup of 50. Results are shown for the current detector (black circles, green triangles), and the upgrade detector (red squares, blue inverted triangles); with Tracker modules at 100% efficiency (black circles, red squares), and with dead Tracker modules as explained in the text (green triangles, blue inverted triangles). Ratio of the track fake rates with dead Tracker modules to the track fake rate with Tracker modules at 100% efficiency as a function of η for default tracks in a $t\bar{t}$ sample with (middle-right) zero pileup, and (right) an average pileup of 50. Results are shown for the current detector (blue circles), and the upgrade detector (red squares).

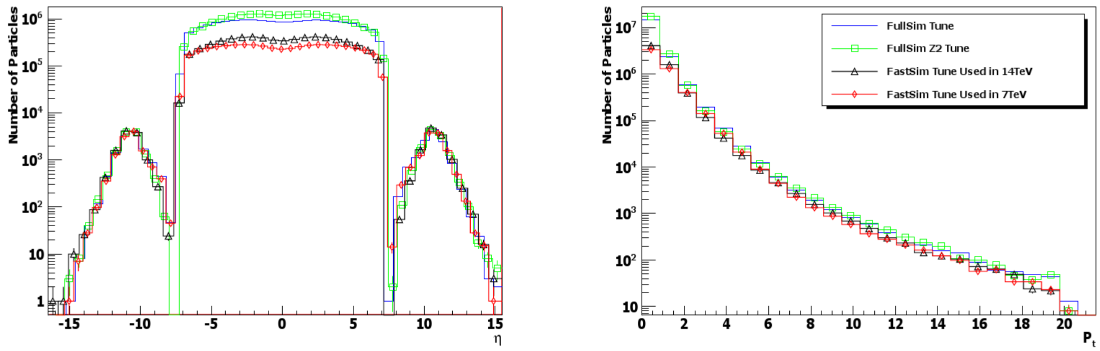

Figure 5: Number of generator level particles for 100,000 events generated with several tunes of the Minimum Bias Pythia event generator.

Dr. Brownson was also one of two Data Managers for the upgrades on CERN's Tier-2 storage element. He created the workflows to generate the Monte Carlo datasets that were used by CMS Data Operations to produce samples for the upgrade studies.

3.4.2 Upgrade Hardware

During the last grant period, the UPRM Group worked on several hardware projects mainly related to the design of an upgraded pixel detector. In addition, another state-of-the-art hardware project was related to Silicon Photomultiplier detectors for time-of-flight measurements of unprecedented resolution.

Improved pixel sensors for the CMS upgrade were in development both at PSI and at Fermilab and we were involved in both efforts. Dr. Lopez and his student participated in a beam test at CERN during the 2010 summer which was designed to measure the absolute efficiency of new pixel sensors developed by PSI. Both irradiated and non-irradiated sensors were tested. These studies were continued at PSI using a radioactive source and a scintillation counter trigger. In a continuation of the work carried out before 2010, the relative efficiency of pixel sensors as a function of irradiation was measured but this time the trigger counter was used to select only events where the electron from the Sr90 crossed the pixel completely thus giving more accurate results. In addition, better humidity and temperature controls were used and the tests were done at a lower temperature better simulating operating conditions. The results (Fig. 6) indicated the pixels can be operated at higher radiation levels than expected. With increased radiation the bias voltage must be increased but collection saturation occurs at sufficiently low bias voltages. Although the charge collected decreases with radiation it is still well above the noise level at saturation even at the highest fluences applied.

In addition to relative efficiency, during these tests the risetime of the pixel pulse and the leakage current due to the bias voltage were measured. An alternative, more accurate method of analysis for determining the risetime was developed by UPRM. The risetime was found to increase with radiation but remained within acceptable limits even at the highest irradiation levels.

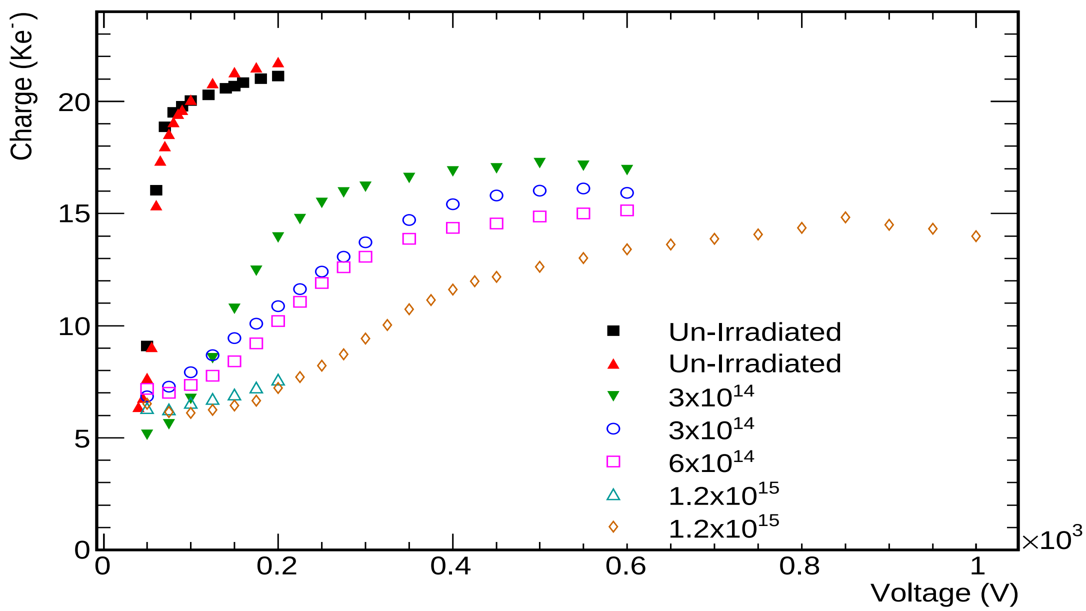

Figure 6: Relative pixel efficiency (measured in terms of charge collected per mono-energetic photon absorbed (Sr90 source)) as a function of bias voltage for sensors subjected to different radiation levels (in units of n_{eq}/cm^2). Unirradiated sensor results are included for comparison.

The same was found for the leakage current. A UPR graduate student (Joaquin Siado) presented these results at the APS Spring meeting in March, 2012.

At Fermilab's SiDet facility, Dr. Zatserklyaniy designed and assembled a pixel sensor test facility which includes a scintillator counter trigger. This station is capable of testing sensors at low temperature (-20^oC). It includes Peltier, fluid and Vertex chillers, and dry nitrogen flow. The box is equipped with a control system which provides temperature and humidity monitoring and control. Dr. Zatserklyaniy used this test station to carry out a study of new silicon strip modules. The results were presented at a CMS Collaboration meeting in Alushta (Ukraine) in May, 2011.

Another major project by Dr. Zatserklyaniy was related to the very forward proton detector. This detector will be installed 240 m downstream of the CMS interaction point. The physics goal is to measure the reaction $p + p \rightarrow p + X + p$ where X may be a Higgs boson. The X state will be identified by the main CMS detector. Good timing resolution is necessary to reduce background by making sure that both protons come from the same interaction and will allow to better identify the vertex measured by the CMS detector. The proton detector will use prompt Cerenkov light coming from quartz bars.

This development project consisted of two beam tests of state-of-the-art silicon photo-multipliers(SiPM) manufactured by two companies, STMicroelectronics and Hamamatsu. Work was done on all phases of the beam tests at the Fermilab Test Beam facility including the analysis of the data. A time resolution of better than 30 ps was obtained for a SiPM-based time-of-flight system.

Related to this project were studies of a novel technique for measuring SiPM timing using the DRS4 digital oscilloscope board developed by the Paul Scherrer Institute. The measurements were done using a picosecond laser source. Dr. Zatserklyaniy improved the analysis by developing a model of the SiPM as a charging/discharging capacitor. The model includes time jitter and scintillator decay time. Fitting of the more realistic model pulse function significantly improved the time resolution. Dr. Zatserklyaniy later improved this analysis using the results of beam tests carried out at the Fermilab Meson Test Beam Facility. The improvement resulted from the development of a waveform analysis algorithm for the DRS4. The DRS4 was used to read out the signals from SiPM photodetectors in a test of the response of plastic scintillator tiles to proton and electron beams. With this technique a time resolution of 42 ps was achieved for SiPM-SiPM pairs. The results were reported by Dr. Zatserklyaniy at the TIFF Conference in Chicago (June, 2011) and more importantly were published in three NIM articles. Although a collaborative project, he played a leading role in this work.

Another UPR graduate student (Indira Vergara) carried out several projects at PSI related to the detailed design of the changes to the microelectronic circuits (the readout chip or ROC) that need to be implemented in order to change from an analog readout scheme to a digital readout scheme which will be needed for the upgraded pixel detector. This change is necessary in order to handle the increased data throughput that will occur at higher luminosity. Two of the new circuits that will be added to the pixel readout chip (ROC) are a 5-stage ring oscillator and a 4-bit serializer. The ring oscillator sends the clock signal to the serializer which should be able to work at 160 MHz. Indira carried out a computer simulation of the performance of the circuits designed in collaboration with PSI. Once a design for the ring oscillator was vetted via the simulations, three test chips were produced. Indira then carried out a study of their actual performance as a function of irradiation. The samples were irradiated with ten doses of 5 Mrad each using a 60Co source. Performance was measured after each dose. The conclusion was that the degradation of the frequency with irradiation is within acceptable limits (Fig. 7). With respect to the serializer simulation, this was very important in determining optimized operation parameter values to reproduce accurate measurements and was an important contribution to this design effort.

Another important project carried out by UPRM confirmed the desirability of using thermal paste to improve the heat dissipation from the pixel modules to the carbon fiber structure where they will be mounted in the upgrade detector. Precise temperature measurements at different points of the pixel detector structure showed that under operating conditions with the carbon fiber at 10^oC the pixel sensor temperature was reduced by 5^oC (from 18.5^oC with no thermal paste to 13.5^oC with thermal paste.)

The CMS pixel cooling system will be converted to use CO2 as the cooling agent in a dual phase system. In order to work properly the gas to liquid ratio needs to be within certain limits. Another UPRM project concerned the development of a device to monitor this ratio. PSI had proposed the use of an optical monitoring system where a light source (LED) and a light detector (photodiode) are mounted on opposite sides of a transparent (quartz) piece of tubing. The idea is to use the photodiode signal to monitor the presence or absence of bubbles in the cooling agent stream. The bubbles cause fluctuations in the signal which are much smaller for the case of all gas or all liquid. Either of these extreme states is an alarm situation as cooling performance will

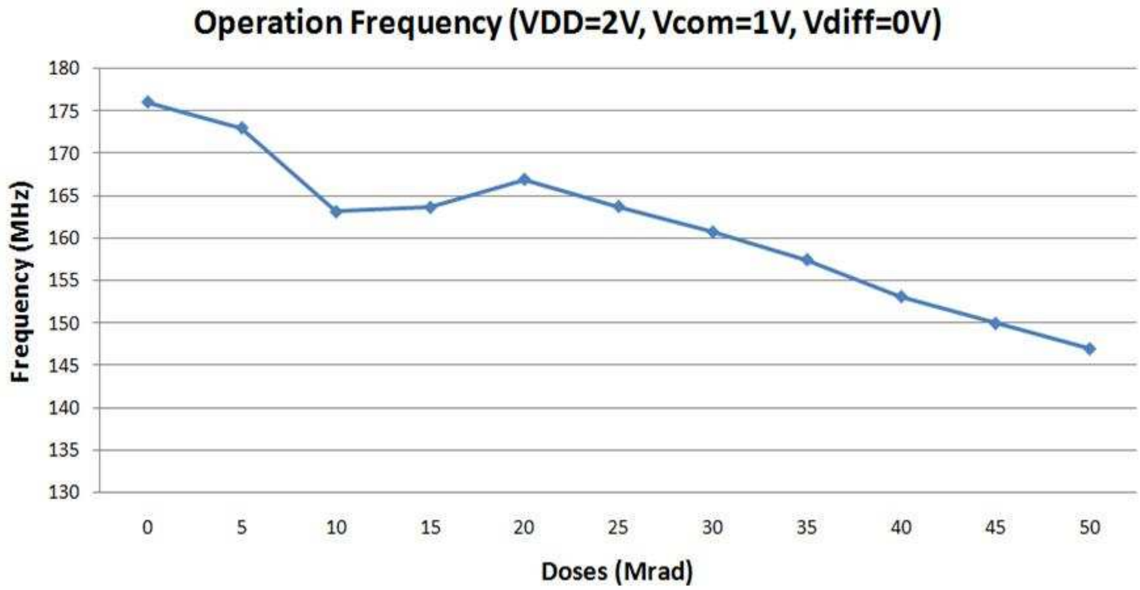

Figure 7: Average optimal operating frequency for three samples of a ring oscillator circuit submitted to various 5 Mrad radiation doses.

deteriorate seriously under such conditions. Our undergraduate student, Joseph Cordero, carried out a project that demonstrated the viability of such a system experimentally by developing an algorithm that could analyze the photodiode signal correctly.

3.5 CMS Analysis

3.5.1 Motivation

CMS is a general purpose experiment [1] designed to cover a wide range of physics topics including Standard Model precision measurements, heavy flavour physics, new physics searches, etc. Since the beginning of the data taking (2011), the experiment has contributed to heavy flavour physics in several B physics measurements and new observations ([3], [4], [5], etc.). Given the time scales of the upcoming B factories, SuperKEKB [6] and SuperB [7], and the LHCb upgrade [8], CMS will continue well positioned to produce new and interesting results on heavy quark physics until at least 2017-18. SuperKEKB and SuperB will collect a very large sample of B meson decays (50 and 75 ab^{-1} respectively) but this will be only after the year 2020. LHCb, the specialized b-physics experiment [9] at the LHC, is expected to record $10\ fb^{-1}$ of B-meson decays by the year 2017.

Dimuon triggers combined with precise tracking and vertexing capabilities are used to trigger heavy quark physics at CMS. The trigger is very flexible and has been adapted to the increasing luminosity by making use of invariant masses, decay lengths, distance of closest approach, transverse momentum and rapidity. The trigger bandwidth is mostly limited by the availability of Tier-0 resources rather than the trigger and readout capacity. In addition to collect data at the nominal rate of 300 Hz of the baseline trigger and to reconstruct that high priority data without any delay, CMS has implemented a ”data parking” scheme to store around 100 Hz of heavy flavour physics triggered data on tape and delay the event reconstruction until the first long shutdown (2013-14).

CMS is a detector with good mass resolution, an accurate pixel detector and an excellent muon system; however, the mass and decay time resolutions are somewhat worse than LHCb, which puts constraints on some physics channels with very low statistics. LHCb (mainly forward coverage) and CMS (mainly central coverage) are kinematically complementary which is an important asset for obtaining a complete picture of heavy flavour physics at the LHC. Due to the good z-coordinate resolution of the pixel detector, the heavy flavour channels detected at CMS are relatively insensitive to pileup.

In the meantime (mainly before 2017) CMS will take full advantage of the large collected integrated luminosity, $25fb^{-1}$ by the end of the 2012 8 TeV pp run and expected to be $90fb^{-1}$ by the 2015-17 run at 13-14 TeV, to search for new physics on rare decays ($\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$, $\tau^+ \to \mu^+\mu^-\mu^+$, etc.), make precision measurements, search for new b-baryons resonances and new decay modes, etc. This large sample also provides a good opportunity to confirm some of the new exotic charmonium states (around 15) discovered in the last decade that are not predicted by the Standard Model.

Experimental detection of rare decays (like $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$) open a window into new physics since these decays are highly suppressed in the Standard Model (SM) and may be mediated by “exotic” particles involving physics beyond the standard model (BSM) to be visible.

The exclusive baryonic $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$ decay proceeds via the Flavor-Changing Neutral Current (FCNC) $\mathbf{b} \to s$ transition where the bottom (b) and the strange (s) quarks carry the same charge but different flavor. Particle decays induced by FCNC processes are forbidden at tree level in the standard model (SM) and must occur through higher order loop level (penguin/box diagram shown in figure 8-a) and are therefore highly suppressed. At the same time, these channels are also good candidates [10] for new physics BSM (figure 8-b) such as supersymmetry, light dark matter, four generation, etc. The measurement of branching ratios is one of the very useful tools in looking for new physics. SM prediction for the FCNC’s $\mathbf{\Lambda_b^0}$ branching fraction is $B(\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-) = [4.0 \pm 1.2] \times 10^{-6}$ [11]. Any deviation from this prediction makes this channel an excellent candidate to explore potential new physics beyond the Standard Model.

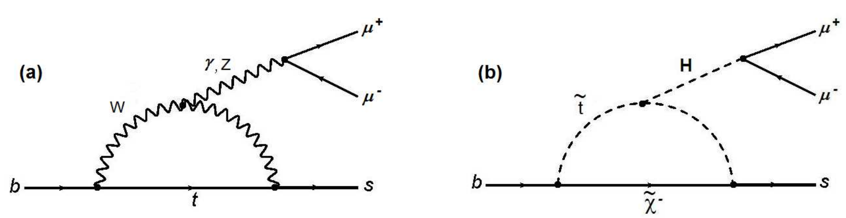

Figure 8: FCNC $\mathbf{b} \to \mathbf{s}\mathbf{l}^+\mathbf{l}^-$ decay. (a) SM one-loop. (b) BSM one-loop.

3.5.2 Preliminary Analysis

During this grant period, our group carried out preliminary studies using the 2011 dataset at $\sqrt{s}$=7 TeV to measure the absolute $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$ branching ratio. In order to show that we have all the tools needed for this analysis, our search strategy consisted mainly in reconstructing first the copious "charmed" $\mathbf{\Lambda_b^0}$ decays and then reconstructing our candidate $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$ sample. In addition to take a close look at the underlying dimuon invariant mass distribution in this sample, we needed to work in finding isolated $\mathbf{\Lambda_b^0}$ vertex (no other tracks from this vextex) to remove the "charm" and "bottom" contributions.

We started the analysis by looking for $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$, a Cabibbo Favoured mode shown in figure 9 which is used as the normalization mode in this measurement, and at the same time

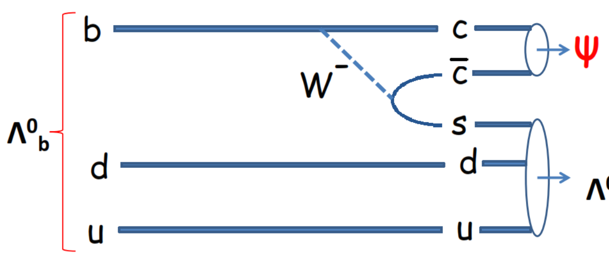

Figure 9: Cabibbo favoured $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$ decay.

subtracted from the "penguin" decay signal we are searching for. The absolute branching ratio is determined by:

$$\frac{B(\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-)}{B(\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi)} = \frac{N_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0}\mu^+\mu^-}}{N_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0 J}/\psi}} \times \frac{1}{\epsilon} \times B(J/\psi \to \mu^+\mu^-)$$

where $N_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0}\mu^+\mu^-}$ and $N_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0 J}/\psi}$ are the number of reconstructed yields for $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0}\mu^+\mu^-$ and $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$ respectively, $\epsilon = \epsilon_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0}\mu^+\mu^-}/\epsilon_{\mathbf{\Lambda_b^0}\to\mathbf{\Lambda^0 J}/\psi}$ is the relative reconstructed efficiency from Monte Carlo simulations and the related J/ψ branching fractions (B($J/\psi \to \mu^+\mu^-$) = (5.93±0.06)% and B($\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$) = 0.0706%) are taken from the Particle Data Group Review [12].

The dimuon CMS data skim (onia) is the dataset we used to reconstruct $\mathbf{\Lambda_b^0}$ decays, which mainly consisted in requiring that the $\mu^+\mu^-$ and the $\mathbf{\Lambda^0}$ be detached from the primary vertex and the $\mu^+\mu^-$ satisfy the experiment high level trigger (HLT) for displaced low dimuon mass. The topology of the decay is shown in figure 10, which also shows the requirement that the reconstructed $\mathbf{\Lambda^0}$ total momentum point to the $\mu^+\mu^-$ vertex which in this analysis is considered as the $\mathbf{\Lambda_b^0}$ candidate. Our starting sample consisted of around 25 million reconstruced $\mathbf{\Lambda^0} \to \mathbf{P}\pi^-$ decays (figure 11-a) from where the $\mathbf{\Lambda_b^0}$ is extracted by combining $\mathbf{\Lambda^0}$ with $\mu^+\mu^-$ from J/ψ candidates. The preliminary $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$ candidates sample is shown in figure 11-b where we have also required that neither of our candidates tracks ($\mu^+\mu^-$ and $P\pi^-$) belong to the primary vertex.

Based on our $\mathbf{\Lambda_b^0} \to \mathbf{\Lambda^0 J}/\psi$ sample and on CDF results, we expect to observe in the 2011 pp run around 20 events assuming that the relative reconstruction efficiency is 30%.

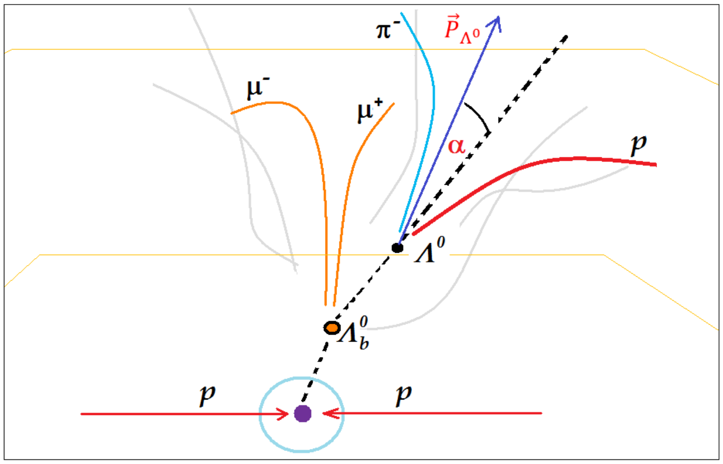

Figure 10: $\mathbf{\Lambda_b^0} \rightarrow \mathbf{\Lambda^0}\mu^+\mu^-$ decay topology.

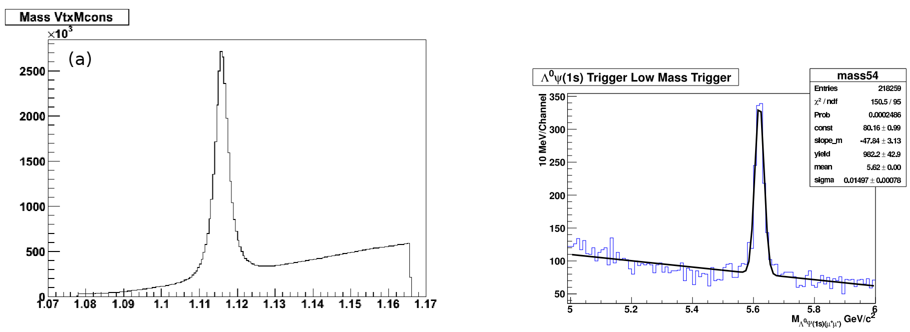

Figure 11: Preliminary reconstructed (a) $\mathbf{\Lambda^0} \rightarrow \mathbf{P}\pi^-$ (b) $\mathbf{\Lambda_b^0} \rightarrow \mathbf{\Lambda^0 J}/\psi$ decay sample.

This preliminary analysis, based on the 2010 and 2011 full MuOnia dataset, was presented by Dr. Mendez in the Exclusive B decays working group and in the CMS B workshop at CERN.

3.6 Statistical Analysis

Dr. Rolke and Dr. Lopez continued their collaboration on the development of methods for the statistical analysis of High Energy Physics data. During this last grant period, the emphasis was on the significance of discovery claims at the LHC. In particular, major progress was made on the issue of determining the location and size of a signal for which they developed the semi-parametric method which is described in the following.

Almost all data sets encountered in High Energy Physics (HEP) have events that were generated by different mechanisms. Interest often focuses on one of these mechanisms, what we will call the signal. By judicious cutting on auxiliary variables it is often possible to bring out the signal, that is, to improve the signal to noise ratio, but it is usually not possible to eliminate the noise, or background events, altogether. In many cases the researchers want to estimate the parameters involved in the signal such as the location and the width of an invariant mass peak, together with their statistical errors. In order to do so, they need to find a model for the data, and because the data still contains background events the model usually has the form of a mixture distribution. In practice it often turns out to be fairly straightforward to find a parametric description for the signal density, for example from theoretical considerations. In contrast it is often very difficult to model the background density, and the typical approach is one of trial and error: fit a number of shapes until a satisfactory one is found. This approach has several drawbacks: (i) it is quite time consuming, (ii) different researchers might end up with different parametrizations, (iii) it is hard to know when to stop in order not to overfit the data and (iv) it is almost impossible to gauge the systematic error of an incorrectly specified background on the parameter estimates.

There are, however, other solutions to the problem of estimating a density, namely the so-called nonparametric density (NPD) estimators. A number of such methods are known, such as kernel methods, nearest neighbor methods, the method of penalized likelihood and others. We could apply any of these methods to HEP data but unfortunately they do not yield the parameters that are the ultimate goal of the fitting process.

Although our work on this method had begun previously, during the last grant period we further developed the semiparametric method that combines traditional parametric fitting with nonparametric density estimation. We used a parametric description for the signal, modeled the background nonparametrically and combined these ingredients into one fitting function.

This method is made especially useful by two features of HEP data. First, we often have available a sample of pure background events, either by eliminating potential signal events by cutting on auxiliary variables or from Monte Carlo. This will allow us to employ the most powerful techniques developed for NPD estimation, for example the methods for choosing the optimal amount of smoothing. Secondly, data in HEP is usually supported on a finite interval. This normally would lead to the so-called boundary problem in NPD density estimation, a seemingly innocuous problem for which to date no single solution is known. However, because in HEP we are not interested in the NPD estimate itself but in the signal parameters, we can solve this problem easily by transforming the data. As our simulation studies show this solution of the boundary problem can be applied to wide variety of problems and leads to correct estimates of the parameters and their errors.

We performed a number of simulation studies that showed that this method is quite competitive, almost as good as using the (in real life unknown) true parametrization and superior to using an almost correct parametrization. Moreover, because the nonparametric density estimate depends smoothly on the bandwidth, it is easy to do a sensitivity study and gain insight into the systematic error caused by different background shapes.

The results of this work were published in Nuclear Instruments and Methods A. The detailed reference can be found in Section 4, the list of Group Publications.

Another major contribution was made by Dr. Rolke who served as a consultant to the CMS Statistics Committee from April, 2011, until the end of the grant period. He participated in the weekly meetings of the committee and gave his advice on a large number of different topics. He wrote a number of CMS internal documents, for example, concerning the statistical bootstrap and its uses, issues related to model selection such as the advantages of the likelihood ratio test vs. the F test and the difficulties related to parametric fitting of probability density functions.

4 Group Publications

Limiting ourselves only to publications in refereed journals, UPRM Group members appeared as authors in 55 FOCUS publications, 100 CLEO publications and all CMS publications after they were accepted as members of the collaboration.

Here only publications in refereed journals where group members have had a major role are listed.

- W. A. Rolke, *et al.*, *Confidence intervals and upper bounds for small signals in the presence of background noise*, Nucl. Instrum. Meth. **A458** (2001) 745.
- J. M. Link, *et al.* (FOCUS Collaboration), *Measurements of Ξ_c^+ branching ratios*, Phys. Lett. **B571** (2003) 139.
- J. M. Link, *et al.* (FOCUS Collaboration), *Search for rare and forbidden 3 body dimuon decays of the charmed mesons D^+ and D_s^+*, Phys. Lett. **B572** (2003) 21.
- W. A. Rolke, *et al.*, *Correcting the minimization bias in searches for small signals*, Nucl. Instrum. Meth. **A503** (2003) 617.
- W. A. Rolke, *et al.*, *Limits and confidence intervals in the presence of nuisance parameters*, Nucl. Instrum. Meth. **A551** (2005) 493.
- J. M. Link, *et al.* (FOCUS Collaboration), *Search for a pentaquark decaying to Cascade-pi-*, Phys. Lett. **B661** (2008) 14.
- A. Ronzhin, *et al.*, *Tests of timing properties of silicon photomultipliers*, Nucl. Instrum. Meth. **A616** (2010) 38.
- A. Ronzhin, *et al.*, *Development of a 10-ps level time of flight system in the Fermilab Test Beam Facility*, Nucl.Instrum.Meth. **A623** (2010) 931.
- J. Lundberg, *et al.*, *Limits, discovery and cut optimization for a Poisson process with uncertainty in background and signal efficiency: TRolke 2.0*, Comput. Phys. Commun. **181** (2010) 683.
- A. Ronzhin, *et al.*, *Waveform digitization for high resolution timing detectors with silicon photomultipliers*, Nucl. Instrum. Meth. **A668** (2012) 94.
- W. A. Rolke, *et al.*, *Estimating a Signal In the Presence of an Unknown Background*, Nucl. Instrum. Meth. **A685** (2012) 16.

5 Bibliography

[1] C. C. (S. Chatrchyan *et al.*) (CMS Collaboration Collaboration), *The CMS experiment at the CERN LHC*, JINST **3** (2008) S08004.

[2] G. B. Cerati, *et al.*, *Radiation tolerance of the CMS forward pixel detector*, Nucl. Instrum. Meth. **A600** (2009) 408.

[3] S. Chatrchyan, *et al.* (CMS Collaboration Collaboration), *Observation of a new Ξ_b baryon*, Phys.Rev.Lett. **108** (2012) 252002.

[4] S. Chatrchyan, *et al.* (CMS Collaboration Collaboration), *Measurement of the Lambda(b) cross section and the anti-Lambda(b) to Lambda(b) ratio with Lambda(b) to J/Psi Lambda decays in pp collisions at sqrt(s) = 7 TeV*, Phys.Lett. **B714** (2012) 136.

[5] S. Chatrchyan, *et al.* (CMS Collaboration Collaboration), *Search for B(s) and B to dimuon decays in pp collisions at 7 TeV*, Phys.Rev.Lett. **107** (2011) 191802.

[6] M. Iwasaki (SuperKEKB Accelerator Group Collaboration), *The SuperKEKB accelerator status*, PoS **ICHEP2010** (2010) 519.

[7] G. Finocchiaro (SuperB Collaboration Collaboration), *The SuperB Project*, PoS **HQL2010** (2010) 080.

[8] B. Schmidt (LHCb Collaboration Collaboration), *The LHCb upgrade detector*, PoS **EPS-HEP2011** (2011) 200.

[9] J. Alves, A. Augusto, *et al.* (LHCb Collaboration Collaboration), *The LHCb Detector at the LHC*, JINST **3** (2008) S08005.

[10] T. Aliev, *et al.*, *Exclusive $\Lambda_b \to \Lambda\ell^+\ell^-$ decay beyond standard model*, Nucl.Phys. **B649** (2003) 168.

[11] T. Aliev, *et al.*, *Analysis of the $Lambda_b \to \Lambda\ell^+\ell^-$ decay in QCD*, Phys.Rev. **D81** (2010) 056006.

[12] P. D. G. (J. Beringer *et al.*), *The Review of Particle Physics*, Phys. Rev. D **86** (2012) 010001.