Project Description: U.S. CMS Operations at the LHC

Contents

1 Introduction

In this proposal we request renewal of a Cooperative Agreement (CA) for the U.S. CMS detector operations program. The overarching goal of the proposed activity is to realize the physics discoveries made possible by the investments of the U.S. NSF, the U.S. DOE, and others in the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) at CERN. Although the requested funds will not be used to directly support physics research, they will be used to create the conditions that allow that research to go forward. This document will therefore begin with an overview of CMS's physics goals in Section 1.1 below, along with more detailed discussions of the physics accomplishments from early running of the LHC (see Section 2.1) and the plans for physics analysis during the five-year period for which support is requested (see Section 2.2).

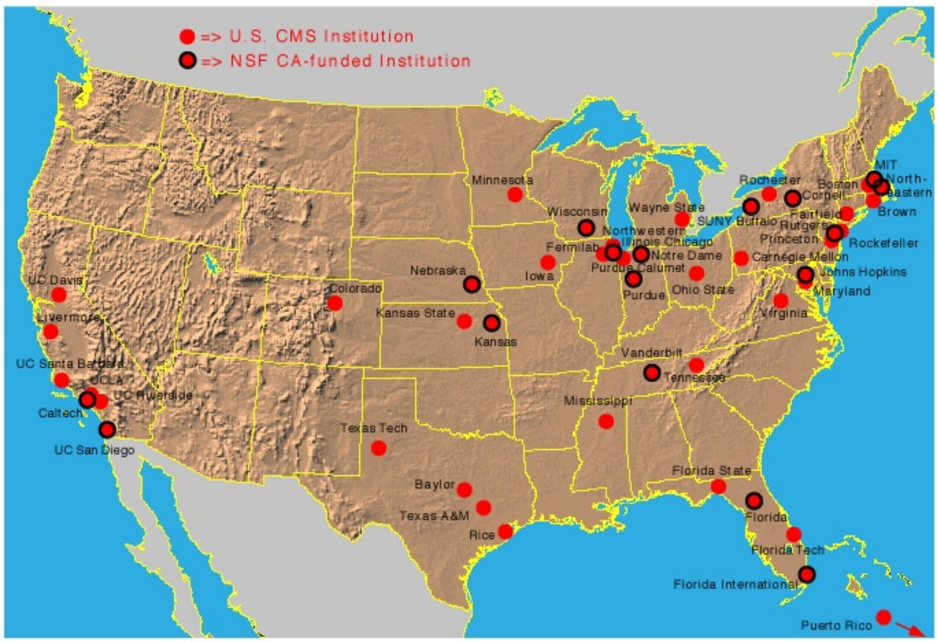

Figure 1: U.S. CMS institutions. The institutions represented by red dots surrounded by black circles will receive funding through this Cooperative Agreement.

The CMS collaboration comprises about 3000 scientists and engineers from 38 countries. U.S. CMS consists of 930 individuals from 49 institutions, geographically distributed as shown in Fig. 1. About 200 of the U.S. participants are graduate students.

About 25% of the U.S. CMS institutes are supported by grants from the NSF Elementary Particle Physics program. These are referred to as NSF "core groups". To exploit fully the ambitious and rich scientific program at the LHC, these researchers, including graduate students excited by the prospects of major discoveries, must have the additional resources required for full participation in all phases of the scientific program during the LHC operational period. This opportunity brings with it ongoing responsibilities: to ensure that the detectors developed and constructed by U.S. CMS physicists continue to be maintained in perfect working order during the operation of the experiment, and that the data is acquired efficiently and made available for analysis by the U.S. members of the CMS collaboration.

Funds from this Cooperative Agreement will provide the additional resources needed by NSF core groups to fully participate in CMS. Since the NSF has expressed a strong interest in supporting analysis computing and developing the data grid as the platform, this CA also provides the funding for the computing activities of universities that have been selected to construct and operate Tier-2 computing centers (explained below), whether the universities' base funding is from NSF or DOE. Figure 1 shows the NSF base institutions and the Tier-2 institutes that will receive funding under the CA renewal.

Sections 3, 4, 5, and 6 of this proposal describe the activities of the groups in Software and Computing, Detector Maintenance and Operations, Upgrade R&D, and Education and Outreach that were carried out under the existing Cooperative Agreement to accomplish these goals, along with the planned activities for the next five years that would be supported by the proposed renewal. Section 7 provides an overview of the budget.

1.1 Physics Goals

The scientific program of the LHC promises to the expand the frontier of our knowledge regarding the fundamental particles, their interactions and the nature of space-time itself. It comprises several thrusts, each aimed at questions of fundamental interest. What is the origin of mass of the elementary particles? Is it the widely cited Higgs Mechanism, or some other as-of-yet undiscovered process? What is the dark matter that accounts for 25% of the mass of the universe? Is it the lightest stable partner predicted in Supersymmetric theories, or one of the other weakly interacting massive particles predicted in other models? What is the origin of the matter-antimatter asymmetry in the universe? Why are there three generations and what gives rise to the observed mixing among them? Is Quantum Chromodynamics really as successful and firmly rooted as it would appear? What more can be learned about its non-perturbative regime? Are quarks fundamental particles, or are they built from smaller constituents? Do we really live in only three dimensions? Can evidence of extra dimensions predicted in some models be found at LHC energies?

The breadth of the LHC physics program and the technical challenge of extracting the physics are nicely illustrated in Fig. 2, which shows the cross sections for various processes, some of which are known and reliably predicted, and other of which are theoretical speculation. Figure 2 also shows the rate at which the indicated signatures will be observed when the LHC reaches its full design energy and luminosity. Particles such as the vector bosons ($W^{\pm}$ and Z^0) and the top quark that were hotly pursued as major discoveries in recent decades will be produced so copiously as to permit detailed precision studies. Indeed they will ultimately become backgrounds to the processes that will be the discovery targets of the LHC program.

The technical challenge inherent in extracting physics from the LHC is immediately apparent when one considers that even though the machine is currently running at only 2% of design luminosity, the *p*-*p* collision rate is 14 MHz. Despite the massive globally-distributed data-processing and storage complexes assembled by the LHC experiments, the maximum sustained recording rate is 300 Hz, meaning that fewer than one in 100,000 events can be retained for detailed analysis offline. The trigger selectivity will need to be increased by two more orders of magnitude by the time the LHC reaches its design luminosity toward the end of the five-year period covered by this proposal. The challenge does not end once the data are logged. Note, for example, that the rates for the important Higgs-discovery processes $H \to \gamma\gamma$ and $H \to Z^0 Z^{(*)0} \to \ell^+\ell^-\ell^+\ell^-$ lie another five to seven orders of magnitude below the maximum trigger rate, so the analysis will require full exploitation of the CMS detector's exquisite selectivity and mass resolution.

1.2 The LHC

After getting off to a slow start as a result of construction delays and a serious magnet incident in 2008, the LHC accelerator team regrouped in 2009 to set the stage for what turned out to be an excellent year in 2010. At this writing (Nov. 2010), in *p*-*p* running at 7 TeV, the LHC has exceeded its goal of $\mathcal{L} = 10^{32}$ cm^{-2} s^{-1} by a factor of two and delivered an integrated luminosity of 45 pb^{-1} to each of the two large experiments. Figure 3 shows the rapid evolution of luminosity delivered to and recorded by CMS since the run began at the end of March 2010. The machine performance has been generally excellent and there is good reason to think that the LHC will reach its design luminosity by the end of the five-year period covered by this proposal.

1.3 The CMS Detector

The overall layout of CMS is shown in Fig. 4. At the heart of CMS sits a 13-m-long, 5.9 m inner diameter, 4-T superconducting solenoid. This solenoid, with its strong field, provides excellent momentum resolution within a compact spectrometer without making stringent demands on muon- chamber resolution and alignment. The return field is large enough to saturate the 1.5 m of iron yoke. Four tracking stations are integrated into the yoke to track muons. Each station consists of several layers of aluminium drift tubes (DT) in the barrel region and cathode strip chambers (CSCs) in the endcap region, complemented by resistive plate chambers (RPCs). This layout ensure robustness and full geometric coverage.

The bore of the magnet coil is also large enough to accommodate the inner tracker and the calorimetry inside. The tracking volume is given by a cylinder of length 5.8 m and diameter 2.6 m. In order to deal with high track multiplicities, CMS employs 10 layers of silicon microstrip detectors, which provide the required granularity and resolution to make precise measurements of the momenta of charged tracks. In addition, 3 layers of silicon pixel detectors are placed close to the interaction region to improve the measurement of the impact parameter of charged-particle tracks, as well as the position of secondary vertices. The EM calorimeter (ECAL) uses lead tungstate (PbWO4) crystals with coverage in pseudorapidity up to $|\eta| < 3.0$. The scintillation light is detected by silicon avalanche photodiodes (APDs)

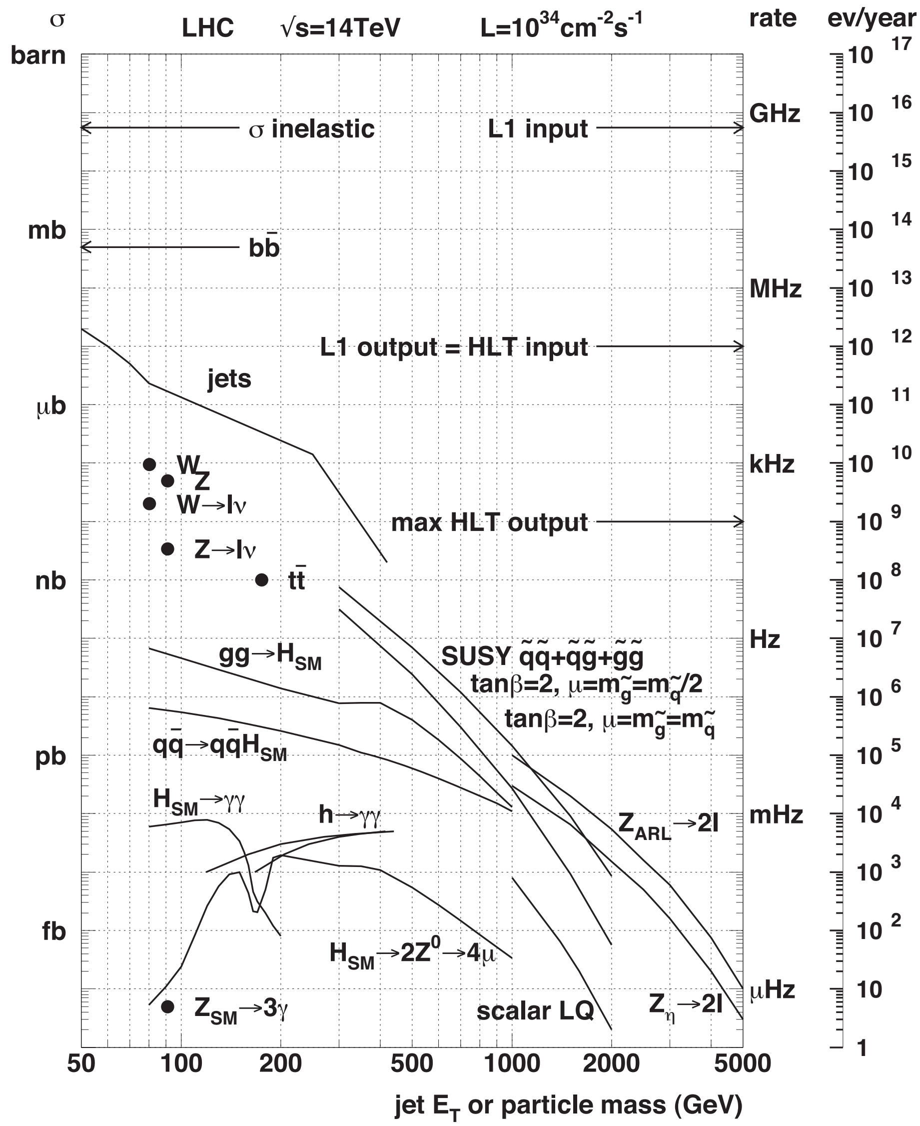

Figure 2: Rates for various physics processes. The curves assume $\sqrt{s} = 14$ TeV, but the situation is qualitatively similar for $\sqrt{s} = 7$ TeV,

in the barrel region and vacuum phototriodes (VPTs) in the endcap region. A preshower system is installed in front of the endcap ECAL for π^0 rejection. The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter with coverage up to $|\eta| < 3.0$. The scintillation light is converted by wavelength-shifting (WLS) fibers embedded in the scintillator tiles and channeled to photodetectors via clear fibers. This light is detected by photodetectors (hybrid photodiodes, or HPDs) that can provide gain and operate in high axial magnetic fields. This central calorimetery is complemented by a "tail-catcher" in the barrel region—ensuring that hadronic showers are sampled with nearly 11 hadronic interaction lengths. Coverage up to a pseudorapidity of 5.0 is provided by an iron/quartz-fiber calorimeter. The

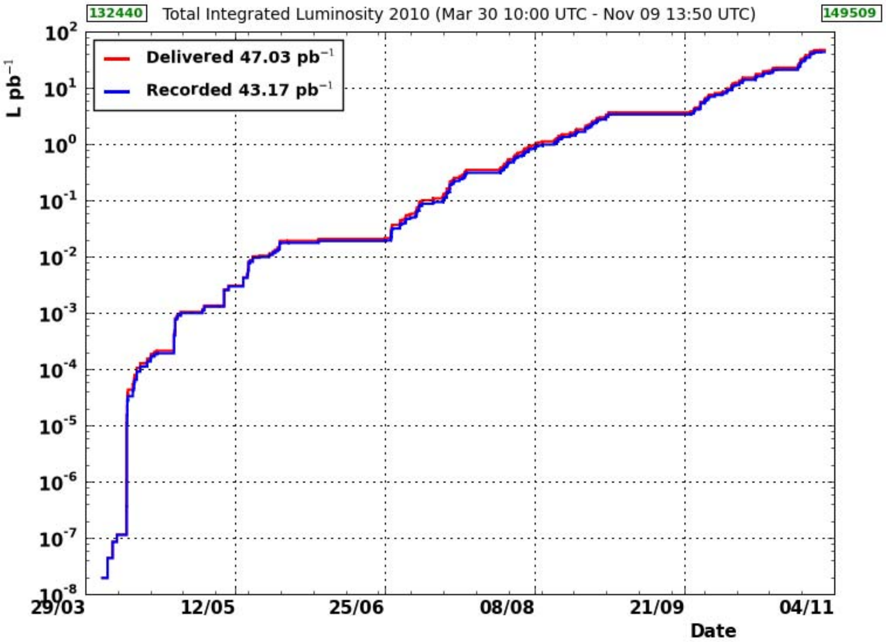

Figure 3: Luminosity delivered to and recorded by the CMS during 2010.

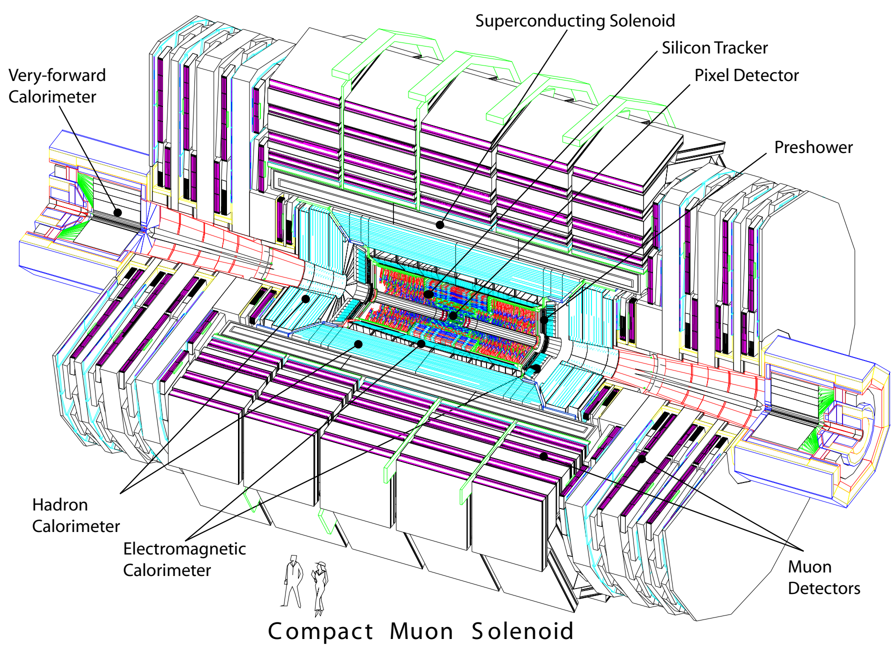

Figure 4: The Compact Muon Solenoid (CMS) Detector

Cherenkov light emitted in the quartz fibers is detected by photomultipliers. The forward calorimeters ensure full geometric coverage for the measurement of the transverse energy in the event.

The overall dimensions of the CMS detector are a length of 28.7 m, a diameter of 15.0 m and a total weight of 14,000 metric tons. The thickness of the detector in radiation lengths is greater than $25X_0$ for the ECAL, and the thickness in interaction lengths varies from 7λ to 11λ for HCAL depending on η.

1.4 The Operations Program

The U.S. CMS Operations Program, which is carried out in accordance with the guidelines set forth in the U.S. CMS Program Management Plan (PMP), is divided into three principal subprograms: i) detector Maintenance and Operations (M&O); ii) Software and Computing (S&C); and iii) Common Operations. The M&O program encompasses activities necessary to ensure proper ongoing operation of the CMS detector as well as research and development activities carried out in preparation for the upgrade of the detector. It does not include the actual construction of the upgrades. The S&C program includes activities designed to facilitate data analysis by U.S. physicists as well as contributions to the general CMS S&C production computing effort. Common Operations supports activities associated with the administration of the Operations program and other activities not directly associated with either S&C or M&O. Common Operations also includes an Education and Outreach (E&O) component, which is a critical part of the work proposed here.

Support for the Operations Program is derived jointly from funds provided by the DOE and the NSF. This proposal requests the NSF portion of those funds. The use of the combined NSF and DOE resources are monitored by the Joint Oversight Group (JOG) composed of representatives of the two agencies. The U.S. CMS Operations Program Manager is Joel Butler of Fermilab. The Deputy Operations Program Manager, Daniel Marlow of Princeton, was selected by the U.S. CMS collaboration in consultation with the management of Fermilab (the U.S. CMS host lab) and with the concurrence of the JOG. Marlow became co-PI of the current Cooperative Agreement with the responsibility for managing the the NSF funds. In keeping with the U.S. CMS PMP Marlow is the PI for this renewal proposal. Catherine Newman-Holmes, Lothar Bauerdick, and James Hanlon (all of Fermilab) are the managers of the M&O, S&C, and Common Operations subprograms, respectively. Daniela Bortoletto of Purdue heads the Upgrade R&D work.

The plan presented here builds on the considerable intellectual and material resources at U.S. universities to create a university-laboratory partnership having outstanding potential for extracting scientific results from CMS. Critically important to this partnership is the operation and further development, in association with computer scientists, of data grids to provide a comprehensive framework for collaborative research and training, supporting coordinated data analysis on an unprecedented scale at facilities at many locations in the U.S. and around the world. This framework presents laboratory and university physicists and their students with unparalleled opportunities to share research results with each other and with other scientists across the globe, including scientists in remote institutions or regions whose intellectual contributions to forefront research would normally be underrepresented.

1.5 U.S. Leadership Roles in CMS

Members of U.S. CMS hold numerous key leadership posts in CMS. Table 1 provides a snapshot of the current situation. In CMS, most leadership posts are term assignments, leading to a steady turnover rate. History shows, however, that U.S. physicists are given a consistently large share of leadership assignments.

Table 1: Key CMS leadership posts currently held by U.S. physicists.

Position	Person	Term
Collaboration Board Chair	Dan Green, FNAL	through 2011
Deputy Spokesperson	Joe Incandela, UCSB	through 2011
Computing Coordinator	Ian Fisk, FNAL	through 2011
Trigger Coordinator	Wesley Smith, Wisconsin	through 2011
Deputy Computing Coordinator	Patty McBride, FNAL	through 2011
Deputy Software Coordinator	Elizabeth Sexton-Kennedy, FNAL	through 2011
Deputy Physics Coordinator	Darin Acosta, Florida	through 2011
Deputy Upgrade Coordinator	Joel Butler, FNAL	through 2011
Run Coordinator	Anders Ryd, Cornell	starting in 2011
ECAL Project Manager	Roger Rusack, Minnesota	through 2010
HCAL Project Manager	Jeff Spalding, FNAL	reappointed for 2011

In addition, U.S. physicists currently hold 8 of the 26 leadership posts associated with the Physics Object and Physics Analysis working groups. Finally, we note that there was strong U.S. involvement, and in most cases U.S. leadership, in the analysis efforts that led to the physics results shown in Section 2.1.

2 Physics

2.1 Results from Early Running

The superb performance of the LHC and CMS in 2010 led to several physics results, which have either been published already [1]- [6], or will soon appear in print [7]-[11]. Still more are well along in the publication pipeline, but have not yet emerged from the internal review process and therefore are not now in the public domain. In what follows, we present highlights of results from CMS thus far. In what follows, ϕ denotes the azimuthal angle corresponding to rotations about the beam axis, and pseudorapidity is denoted by $\eta = -\ln\tan(\theta/2)$, where θ is the polar angle with respect to the beam.

2.1.1 Angular Correlations in pp Physics

One CMS result that recently garnered considerable attention came from studies of near-side angular correlations in high multiplicity events in pp collisions at $\sqrt{s} = 7$ TeV[5]. Figure 5 illustrates the effect. Each entry in these plots represents the difference in η and ϕ of pairs of particles Only particles with p_T values in the indicated ranges are considered. The top two panels show results from minimum-bias events. The region at $\Delta\eta \simeq 0$ and intermediate $\Delta\phi$ is dominated by particle emission from clusters with low transverse momentum, with some contribution from jet-like particle production near $(\Delta\eta, \Delta\phi) = (0, 0)$, due to near-side jet fragmentation and a broad elongated ridge around $\Delta\phi = \pi$ due to fragmentation of back-to-back jets. For the intermediate p_T region of 1 GeV/$c < p_T <$ 3 GeV/c, a more pronounced near-side jet peak and an away-side ridge are visible, due to the enhanced contribution of jet fragmentation to particle production for increasing p_T.

Figure 5c shows two-particle correlations in high-multiplicity events with more than 110 tracks of $p_T > 0.1$ GeV/c. Most correlation structures are similar to those for minimum-bias events (Fig. 5a and 5b). If, however, one requires tracks to fall in the intermediate range (Fig. 5d), an unexpected effect is observed in the data. A clear and significant "ridge"-like structure emergesat $\Delta\phi \simeq 0$ extending to $\Delta\eta \simeq \pm 4$. This novel feature of the data, which is reminiscent of correlations seen in relativistic heavy-ion data, has never been seen in two-particle correlation functions in pp or $p\bar{p}$ collisions and is not predicted in MC simulations. The physical origin of this effect is not yet understood.

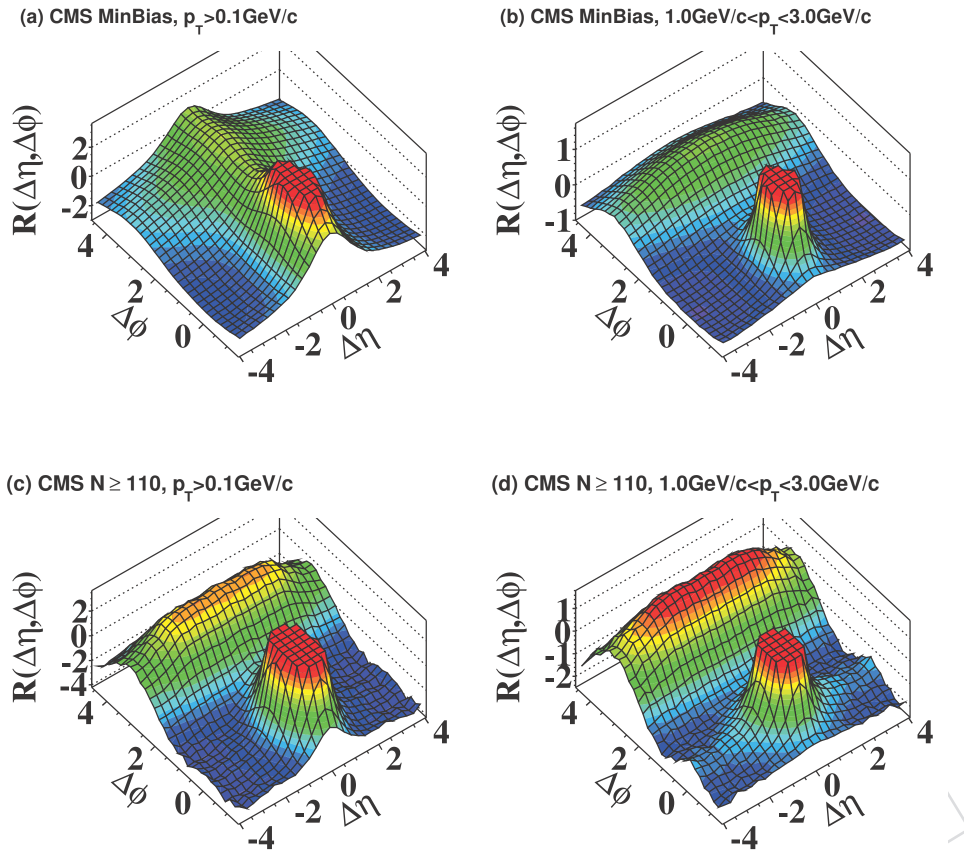

Figure 5: 2-D two-particle correlation functions for 7 TeV pp collisions: (a) minimum bias events with $p_T > 0.1$ GeV/c, (b) minimum bias events with 1 GeV/$c < p_T < 3$ GeV/c, (c) high-multiplicity events with $p_T > 0.1$ GeV/c, and (d) high-multiplicity eventswith 1 GeV/$c < p_T < 3$ GeV/c. The sharp near-side peak from jet correlations is cut off in order tobetter illustrate the structure outside that region.

2.1.2 Dimuon Spectra

The excellent muon identification and measurement capabilities of the CMS detector are illustrated in Fig. 6, which shows the dimuon mass spectrum in the range $2m_\mu < M_{\mu\mu} < 350$ GeV/c^2. Several well-known resonances form prominent peaks and the radial excitations of the heavy-quarkonium S-wave states are cleanly resolved.

2.1.3 Dijets

The steeply falling jet p_T spectrum should be accurately predicted by Quantum Chromodynamics (QCD) in the context of the standard model. Many extensions of the standard model predict the existence of new massive objects that couple to quarks and gluons, and result in resonant structures in the dijet mass. Figure 7 shows the dijet mass spectrum and

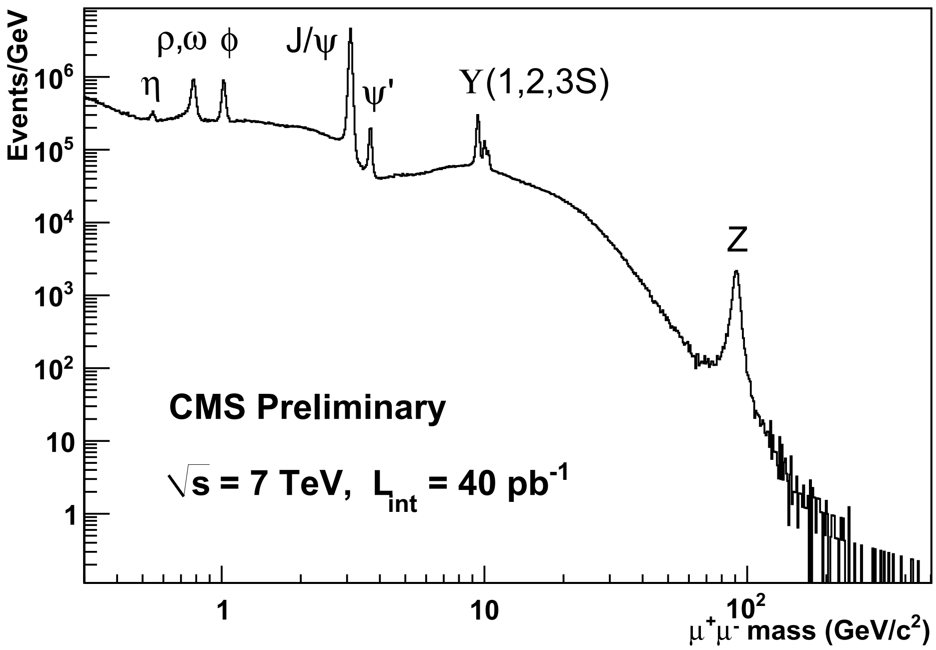

Figure 6: Dimuon mass spectrum in the range $2m_\mu < M_{\mu\mu} < 350$ GeV$/c^2$.

also shows limits on the production of resonances decaying into dijets[6].

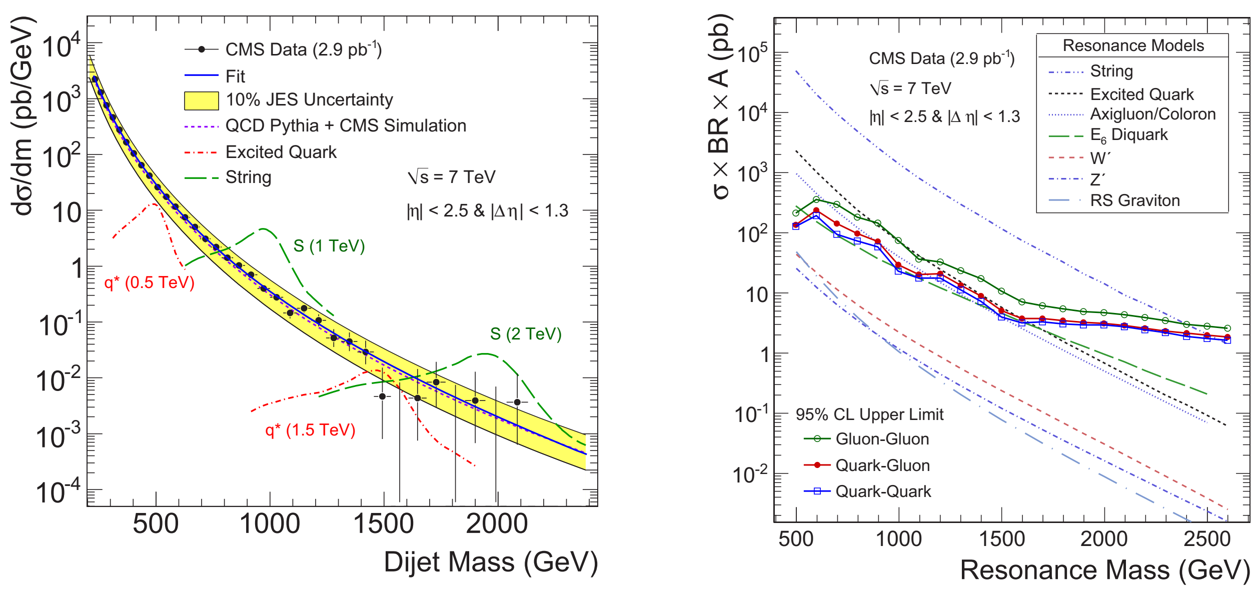

Figure 7: Left: Dijet mass spectrum compared to predictions from Pythia[12]. Right: 95% CL upper limits on cross sections for resonances decaying into dijets as a function of resonance mass. See Ref. [6] for details on the measurement and related theories.

Studies of dijet production can also be used to search for evidence of quark compositeness. In QCD, the jet production rate peaks at large $|\eta|$ because the scattering is dominated by t-channel processes. Several new physics scenarios, including models of quark compositeness, produce a more (or in some cases, less) isotropic angular distribution leading to enhanced jet production at smaller values of $|\eta|$ (see Ref. [9] and references therein for further details). In particular, quark compositeness at an energy scale Λ could result in an η distribution differing from that predicted by QCD. A statistical measure of the extent to which quark compositeness is present in the data is the likelihood difference defined as

$$\mathcal{R}_{LL} = \ln \mathcal{L}_{\mathrm{NP}} - \ln \mathcal{L}_{\mathrm{QCD}}$$

where $\mathcal{L}_{\mathrm{NP}}$ is the likelihood obtained for a fit containing new physics and QCD, while $\mathcal{L}_{\mathrm{QCD}}$ contains only standard model QCD. Figure 8 show limits obtained by CMS in early running.

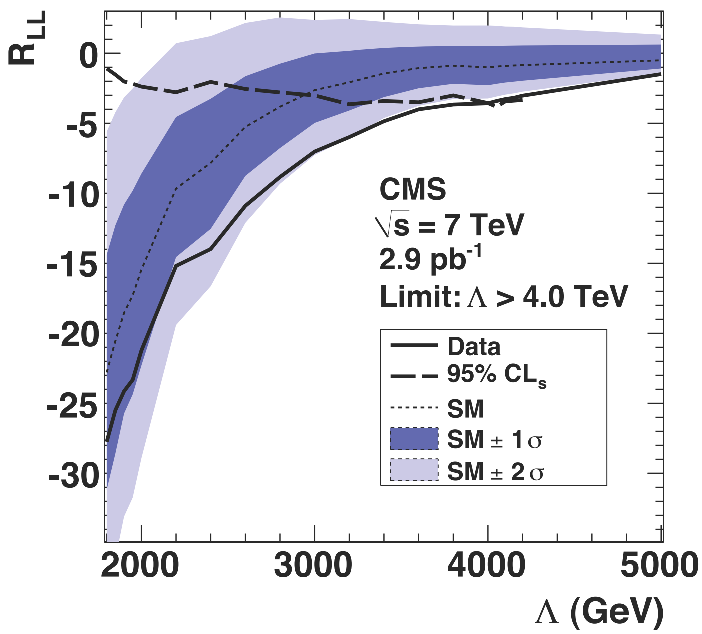

Figure 8: Limits on the contact interaction scale Λ. The plot shows $\mathcal{R}_{LL}$ versus Λ for the data (solid line), the 95% CLs (dashed line), and the SM expectation (dotted line) with 1σ (dark) and 2σ (light) bands.

2.1.4 Inclusive W/Z Production Cross Section

The inclusive production of W and Z bosons is an important benchmark process at hadron colliders. Measurements of $\sigma(pp \to WX) \times \mathrm{BF}(W \to \ell\nu)$ and $\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \ell^+\ell^-)$ test calculations based on higher-order perturbative QCD and modern parton distribution functions (PDFs). They also enjoy potential use as ”standard candle” luminometers for future running. CMS has carried out its first measurement of the rate for these processes using 2.9 pb^{-1} of data[13]. Figure 9 shows the results along with related measurements from other detectors.

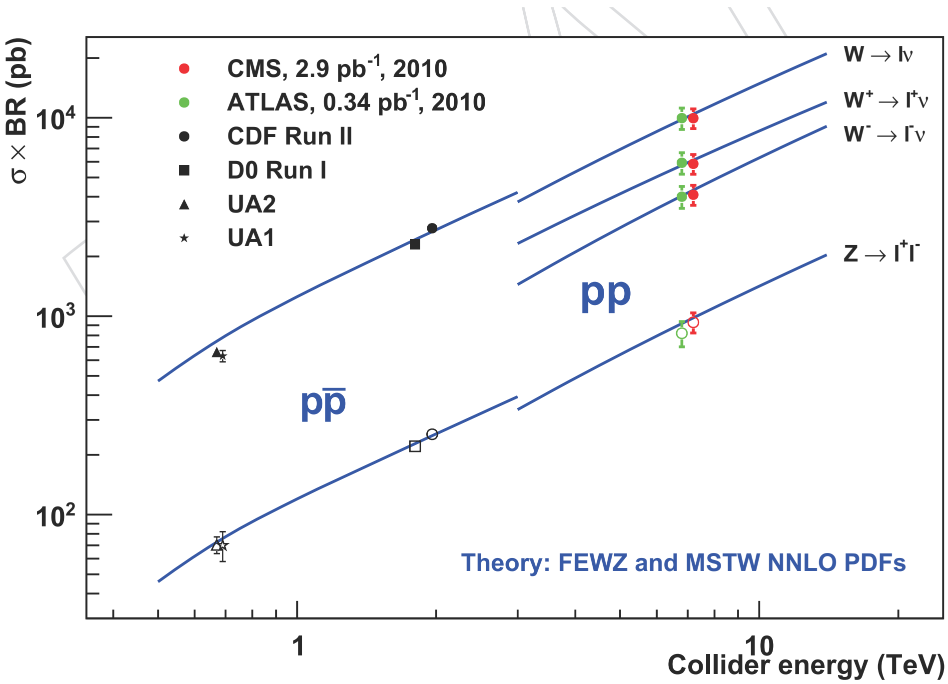

Figure 9: Measurements of inclusive cross sections from CMS, ATLAS and other experiments atlower-energy colliders. The solid symbols represent $\sigma(pp \to WX) \times \mathrm{BF}(W \to \ell\nu)$ and the hollowsymbols represent $\sigma(pp \to ZX) \times \mathrm{BF}(Z \to \ell^+\ell^-)$ The points for ATLAS and CMS are displacedslightly for clarity.

2.1.5 Top Cross Section

Using just 3.1 pb^{-1} of luminosity, CMS has made an early measurement of the cross section for top-quark pair production at $\sqrt{s} = 7$ TeV. This result utilizes thefinal state with two isolated, highly energetic charged leptons, large missing transverseenergy, and two or more jets. Eleven events were observed with an expected background of 2.1 ± 1.0 events. Figure 10 shows that the resulting sample is rich in b-tagged jets, as one would expect in such a sample. For additional details see Ref. [10].

2.1.6 First $ZZ \to 4\mu$ Event

Figure 11 shows what we hope is a tantalizing hint of things to come, an event consistent with $ZZ \to \mu^+\mu^-\mu^+\mu^-$. The masses of the opposite-sign pairings that most closely match to the Z-pair hypothesis are $M_{\mu\mu} = 92.15$ GeV/c^2 and $M_{\mu\mu} = 92.24$ GeV/c^2 and the overall mass is $M_{ZZ} = M_{4\mu} = 201$ GeV/c^2. There is very little other activity in the event. The

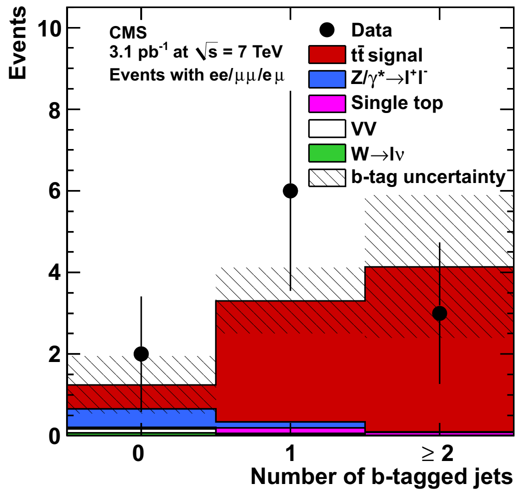

Figure 10: Number of b-tagged jets in events passing all dilepton selection criteria compared to signal and background predictions. The hatched bands reflect theexpected uncertainties on the b-tag efficiency for signal events.

probability of observing an event of this type in $\mu\mu\mu\mu$, $\mu\mu ee$, or $eeee$ is 16% for the 20 pb^{-1} sample that had been analyzed at time this event was observed.

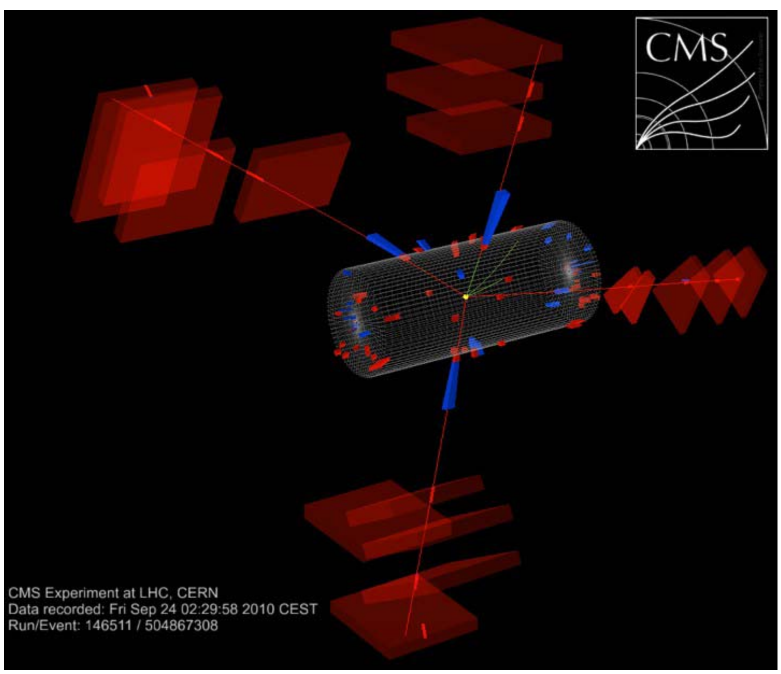

Figure 11: Event display for the candidate $ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$. Tracks having $p_T < 1$ GeV/c have been suppressed.

2.2 Physics Plans and Goals

CMS has established its ability to do physics using the ~ 45 pb^{-1} of data acquired in 2010. The LHC is poised to deliver far larger samples in 2011 and the years that follow. Table 2 shows the LHC's projection for luminosity for the period covered by this proposal (2012-2016). Although such projections obviously involve significant uncertainties, it appears likely that the LHC will deliver several tens of fb^{-1} before the 2016 shutdown. As will be shown below, this represents enough data to answer several of the most important questions in particle physics. Table 2 indicates a shutdown in 2012 to increase the beam energy from its current value of 3.5 TeV to 6.5-7.0 TeV. This is currently the official plan for the LHC, but there is serious discussion of delaying this shutdown until 2013. If adopted, such a plan would alter the profile, but would not have a large impact on the endpoint in 2016.

Table 2: LHC Luminosity Projections. The indicated energies are center of mass values. Figures for 2010 are actual values.

	units	2010	2011	2012	2013	2014	2015	2016
Instantaneous	(10^{34}cm^{-2}s^{-1})	0.02	0.05	Off	0.25	0.55	1.00	Off
Integrated	(fb^{-1})	0.045	2 - 7	2 - 7	10	30	70	70

2.2.1 Higgs Discovery

The discovery of the Higgs boson is one of the most important physics goals of CMS. Figure 12 shows the significance of the expected standard model signal for various luminosities and center of mass energies.. In all cases, the mode providing the highest sensitivity in the indicated mass range is assumed. There is a reasonable prospect for a 5σ detection of a standard model Higgs before the 2012 shutdown and an excellent prospect for a discovery within the period covered by this proposal.

2.2.2 Supersymmetry

Another key physics target is the discovery of the partner particles predicted in supersymmetric models. Such particles offer varied signatures, but the all hadronic and the like-sign dilepton search modes discussed below offer sensitivity to a variety supersymmetric models.

In the all hadronic search, at least three jets within the fiducial region of the detector are required above a minimal jet threshold of $p_T > 50$ GeV/c. Cuts on the scalar sum of transverse energies associated with the jets (H_T) and on the missing momentum are then imposed. Events with isolated muons above 10 GeV/c or isolated electrons above 15 GeV/c are vetoed, to render the search statistically independent from the leptonic searches. Figure 13 shows the sensitivity of the all hadronic search mode. For the 100 pb^{-1} limit curve, $H_T > 400$ GeV and $p_T^{\rm miss} > 225$ GeV/c have been required, whereas for the 1 fb^{-1} curve, the cuts are tightened to $H_T > 500$ GeV and $p_T^{\rm miss} > 250$ GeV/c. Note that a large range of supersymmetric parameter space will be covered in the 2011/2012 time frame, even in the most pessimistic projections of LHC luminosity.

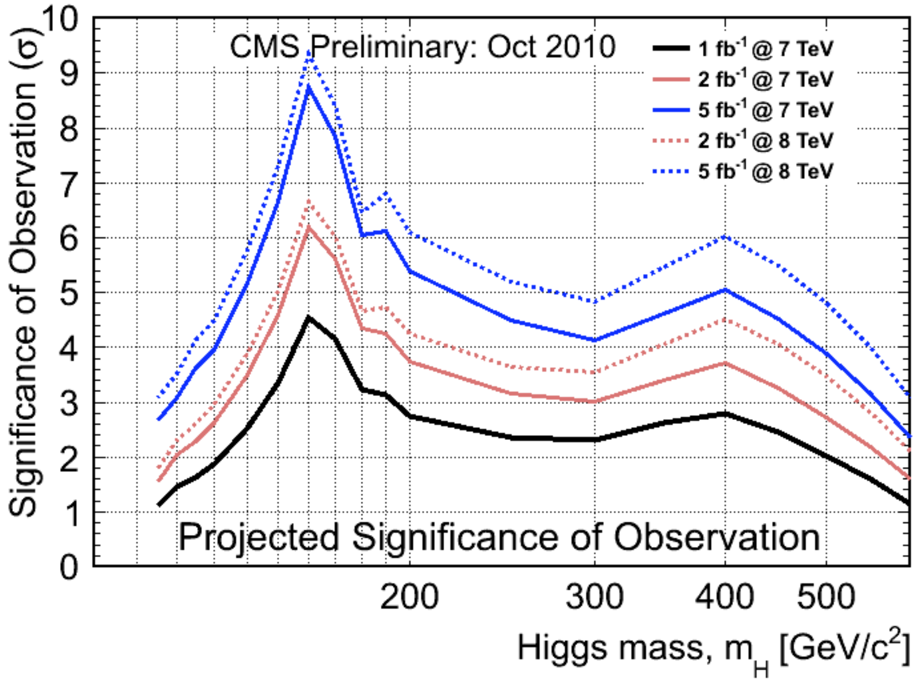

Figure 12: Estimated significance for a Higgs signal as a function of M_H for various energies and luminosities.

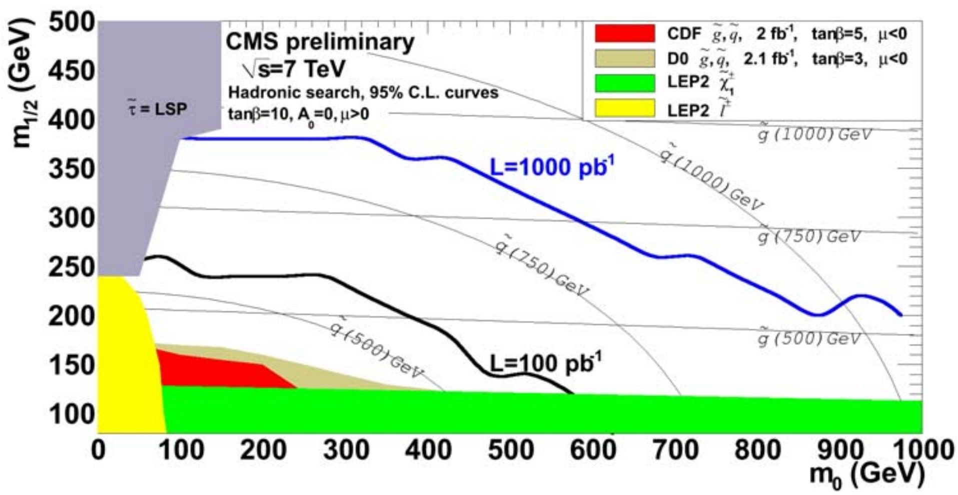

Figure 13: Estimated 95% C.L. exclusion limits for the all-hadronic SUSY search, expressed in mSUGRA parameter space.

The like-sign dilepton search is less inclusive, but has lower background levels. The analysis is performed in three channels: $\mu^{\pm}\mu^{\pm}$, $\mu^{\pm}e^{\pm}$, and $e^{\pm}e^{\pm}$, with the requirement of two like-sign, isolated leptons above minimum p_T thresholds such that both leptons have

$p_T > 10$ GeV/c and at least one has $p_T > 20$ GeV/c. A minimum of three jets above $p_T > 30$ GeV/c is required, and the scalar sum of the transversemomenta of the jets must satisfy $H_T > 200$ GeV. The missing momentum in the event must satisfy $p_T^{\mathrm{miss}} > 80$ GeV/c. Figure 14 shows the sensitivity for the dilepton search. Again, we expect to obtain good sensitivity across a wide range of parameters from the 2011 data set.

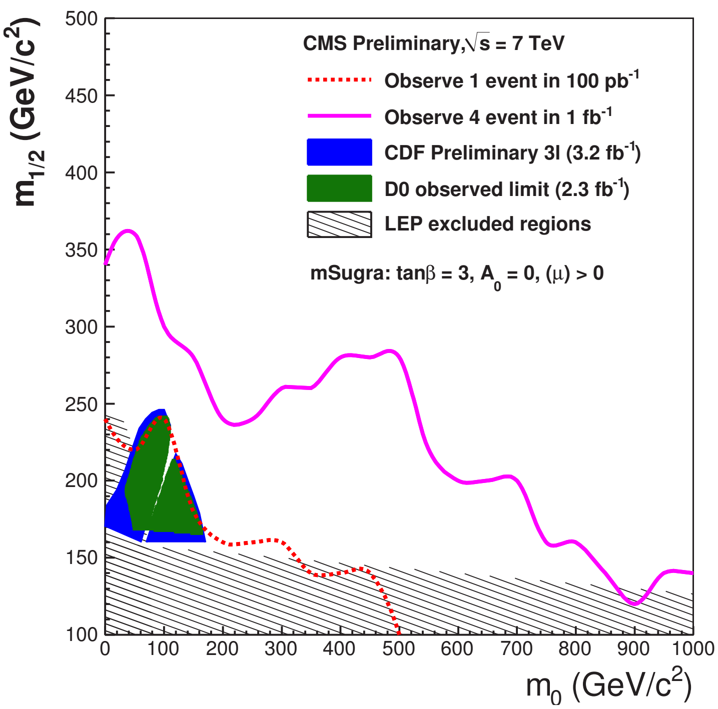

Figure 14: Estimated 95% C.L. exclusion limits for the like-sign dilepton SUSY search, expressed in mSUGRA parameter space.

2.2.3 Exotica

CMS will search for a broad range of signatures from "beyond-the-standard-model" theories. The discovery potential for two such signatures are shown in Fig. 15. The left-hand plot shows the projected significance for Z' and Randall-Sundrum gravitons in the e^+e^- final state. The projected significance values for this mode were obtained by scaling studies done for LHC energies of 10 and 14 TeV. The effective luminosity for this channel will increase by a factor of ten once the LHC begins operating at 14 TeV. The sensitivity obtained to date is already approaching that achieved by the Tevatron searches[14],[15] and should exceed them in early 2011, when the integrated luminosity passes 100 pb^{-1}.

The right-hand plot in Fig. 15 shows the projected significance of a possible monojet signal stemming from graviton production in the $q\bar{q} \to gG$, $qg \to gG$, and $gg \to gG$ processes. Such signatures are predicted in the phenomenological ADD model[16], which addresses the hierarchy problem by introducing a number of extra spatial dimensions, δ. Details of the analysis can be found in Ref. [17].

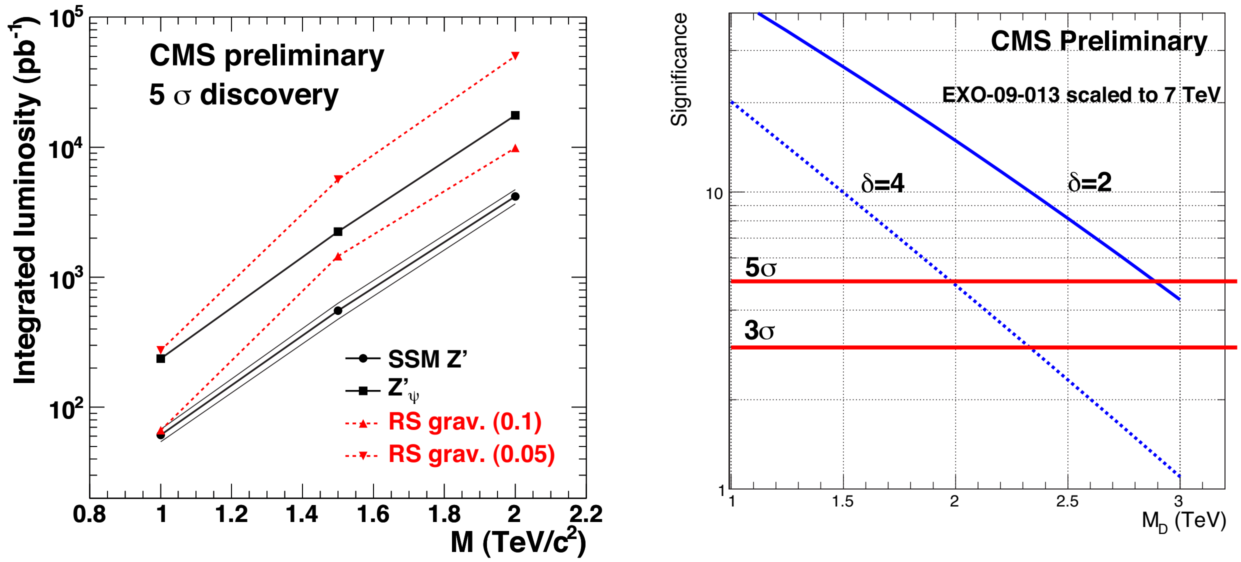

Figure 15: Left: Projected significance for Z' and Randall-Sundrum gravitons in the ee channel at 7 TeV. Right: discovery potential for anintegrated luminosity of 200 pb^{-1}, for large extra dimensions in the monojet channel.

3 Software and Computing

3.1 Tier-2 Computing

Caltech, Florida, MIT, Nebraska, Purdue, UC San Diego, Wisconsin

One of the biggest successes for CMS Computing during the first year of operations has been the adoption of the Tier-2 computing centers for analysis. Tier-2s represent the vast majority of the resources dedicated for analysis and are the primary resource for simulated event production. The generation of simulated events was one of the first large-scale grid workflows, but there was considerable concern how to move the analysis community to the Tier-2 centers. Previous generations of experiments that achieved some level of distributed computing have typically attempted analysis only after a few years of commissioning. LHC experiments needed all the tiers to contribute from the beginning. The Tier-2 centers have served well and are now the most heavily used processing centers in CMS. CMS now has a functioning world-wide computing grid that is serving the needs of physicists and enabling rapid production of physics results.

The "tiered" computing model of the LHC experiments, based on a distributed infrastructure of regional centers, dates back to the MONARC project [18] and evolved with the 2005 CMS Computing TDR [19]. The computing model and resources requests actively evolve with the changing needs of the experiment, but the large- scale structure has not changed. Organized processing of data is concentrated at the Tier-0 and Tier-1 centers. CERN is the host of the Tier-0 center, which is responsible for prompt reconstruction of CMS data and creating an archival copy on tape. About 25% of the CMS processing resources and 50% of the archival storage are at Tier-0. Reconstructed and raw data are transferred to at least one of seven Tier-1 centers hosted by seven member nations of CMS; one Tier-1 center is at Fermilab. Tier-1 centers write a second archival copy; make skims of the data enriched in various physics signals; re-reconstruct older data when improved calibrations, alignments and algorithms become available; and also archive samples of simulated events. The seven Tier-1 centers in aggregate have another 25% of the managed processing resources and 50% of the archival storage.

The Tier-2 centers represent 50% of the total processing resources in 2010, and 40% of the total disk storage. The centers host both real and simulated datasets; these can be transferred from any Tier-1 or Tier-2 site, and high-speed wide-area networking is required to provide new data to physicists quickly. About half of the processing resources are used for data analysis by the 2000 physicists of CMS, while the other half is used for simulations. The use of Tier-2 centers for analysis is one of the largest applications of grid computing both in terms of deployed resources and also in terms of individuals performing computing. The Tier-2s have been efficient and effective computing facilities because they leverage the existing physical infrastructure and operations support at the hosting sites, and they engage the local analysis community. The number of individual submitters to the Tier-2 centers by week is shown in Figure 16.

The disk space at Tier-2 sites is managed by different CMS groups and individuals. Some amount of space, managed by the Analysis Operations group, is set aside for samples

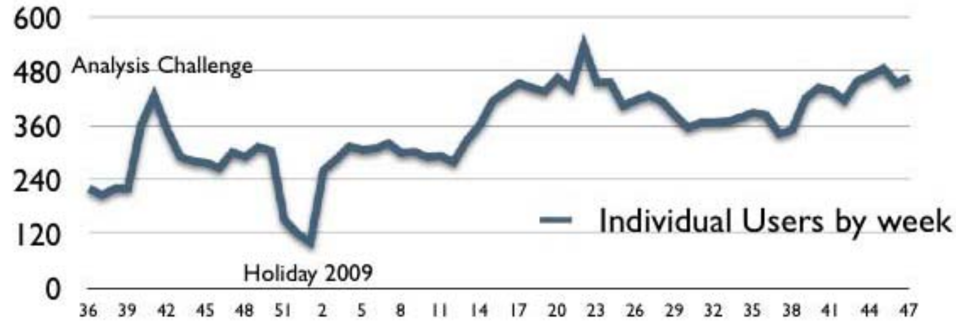

Figure 16: The number of individual analysis submitters is shown by week for mid 2009 through the end of 2010.

of common interest. Some is left under control of the local community, and some belongs to individual physicists to store files in a space that is visible to grid jobs. The bulk of the space is allocated to the physics groups of CMS, for the placement of samples of interest to those groups. Each site hosts at most three physics groups (depending on the size of the site), and each group has space at no more than five sites, limiting the number of communication channels required to manage operations.

There are currently 49 Tier-2 centers serving CMS, and U.S. CMS operates seven of them. These are hosted at Caltech, Florida, MIT, Nebraska-Lincoln (UNL), Purdue, UC San Diego and Wisconsin. The U.S. CMS Tier-2 program was launched in 2005. Funding to construct and operate them was provided by the NSF under the current Cooperative Agreement and through an additional 5 year grant program called DISUN, which stands for Data Intensive Science University Network. The DISUN effort helped the U.S. to contribute its share to development, deployment, and integration activities in CMS. Tier-2 staff have worked in CMS Facilities Operations, Data Operations and Analysis Operations teams; deployment of new storage initiatives; and helped to commission collaborating international Tier-2s.

Prof. Kenneth Bloom, a co-PI of the UNL center, serves as Tier-2 program manager. The U.S. CMS Operations Program supports two FTE system administrators at each site, and currently provides each site with $250K annually to purchase equipment; as discussed below, this is just sufficient to meet U.S. CMS commitments to CMS computing needs. The modest operations support in the program is made possible by relying on operational support from the Open Science Grid (OSG)[20]. OSG validates and packages the underlying grid Infrastructure components as well as provides security and central service support. OSG is the grid peer to the EGI infrastructure in Europe. The OSG and the 7 U.S. CMS Tier-2s form a coherent national infrastructure that is an integral part of a global system.

The nominal size for a U.S. Tier-2 site in 2010 is 7760 HS06 in processing resources and 760 TB of functional storage space. These numbers will continue to grow and evolve as the datasets for analysis grow. These disk pools are large enough for each U.S. site to host data for three physics groups, which means that every CMS physics group has some data at a U.S. site. This has great benefits for CMS as a whole and the U.S. in particular – the experiment has a copy of all of data of interest hosted at reliable sites, and U.S. physicists have easy access to that data.

Since the establishment of the U.S. CMS Tier-2 centers, their performance has been exemplary, setting the standard for the rest of CMS. Several plots illustrating their performance during the 2010 LHC proton run, April 1 through October 31, 2010, are shown in Fig. 17. Every hour, all Tier-2 sites are sent a series of small jobs to test their functionality; sites are expected to pass these tests 80% of the time, and the U.S. sites have passed them well over 90% of the time. The seven sites are heavily used for analysis; they run an average of 4400 user analysis jobs at any time, and complete an average of 33,000 such jobs each day, which is about 40% of the Tier-2 job load across CMS. Across the 49 CMS Tier-2 sites, U.S. sites rank in the top four in number of analysis jobs hosted, and all are in the top eleven. The U.S. users, in turn, are heavy users of the Tier-2 resources across CMS, accounting for about 40% of all jobs, above the U.S. headcount fraction. U.S. sites were the top six contributors to simulation production at Tier-2 sites, and all sites were in the top eight, providing 8.3 million hours of computation time, about half of the total across all of CMS. In aggregate, the sites have transferred 3.2 PB of data from other CMS computing sites; 1.3 PB has come from the Fermilab Tier-1 site, 1.0 PB from other Tier-1 sites, and the remainder from other Tier-2 sites. This data is immediately made available to physicists throughout the collaboration. All of these metrics are a testament to the great reliability, productivity and agility of the sites and their users.

Tier-2 specialists supported by DISUN have helped to commission the network links between the US sites and international Tier-1s and Tier-2s. The increase in the number of potential sources of data has improved the transfer efficiency, increased the flexibility for data access, and made the usage of resources more equitable. The data transfers between European Tier-2s and U.S. analysis facilities, including Tier-2s and Fermilab, during the fall of 2010 are shown in Figure 18. The transfers in each direction have similar maximum and average rates indicating both sides are contributing equally.

The most important role of the U.S. CMS Tier-2 sites is to give U.S. CMS physicists the resources they need to do the best science possible. Every U.S. physicist is granted a quota of disk space at either a U.S. Tier-2 site or at the Fermilab User Analysis Facility. CMS physicists have access to the U.S. Tier-2s to submit analysis jobs which normally run at the site hosting the data. In addition, the U.S. Tier-2 sites provide opportunistic access to computing through OSG supported VOs.

The tiered model of computing, and in particular the placement of the bulk of the analysis resources at the Tier-2 centers, has been a success for CMS, and a critical element of the speed with which the collaboration is producing physics results and the agility with which is can respond to problems. This was proven during the preparations for the ICHEP conference in July of 2010. The bulk of the LHC data was arriving at the very last moment, since the luminosity was increasing so rapidly day by day. In addition, shortly before the conference it was discovered that much of the data had to be re-processed because of a hot calorimeter tower that had not been masked in the first reconstruction. In both cases, the data were successfully moved very quickly to the Tier-2 sites, where physicists were able to complete their analyses efficiently. The majority of the physics results at the conference came from

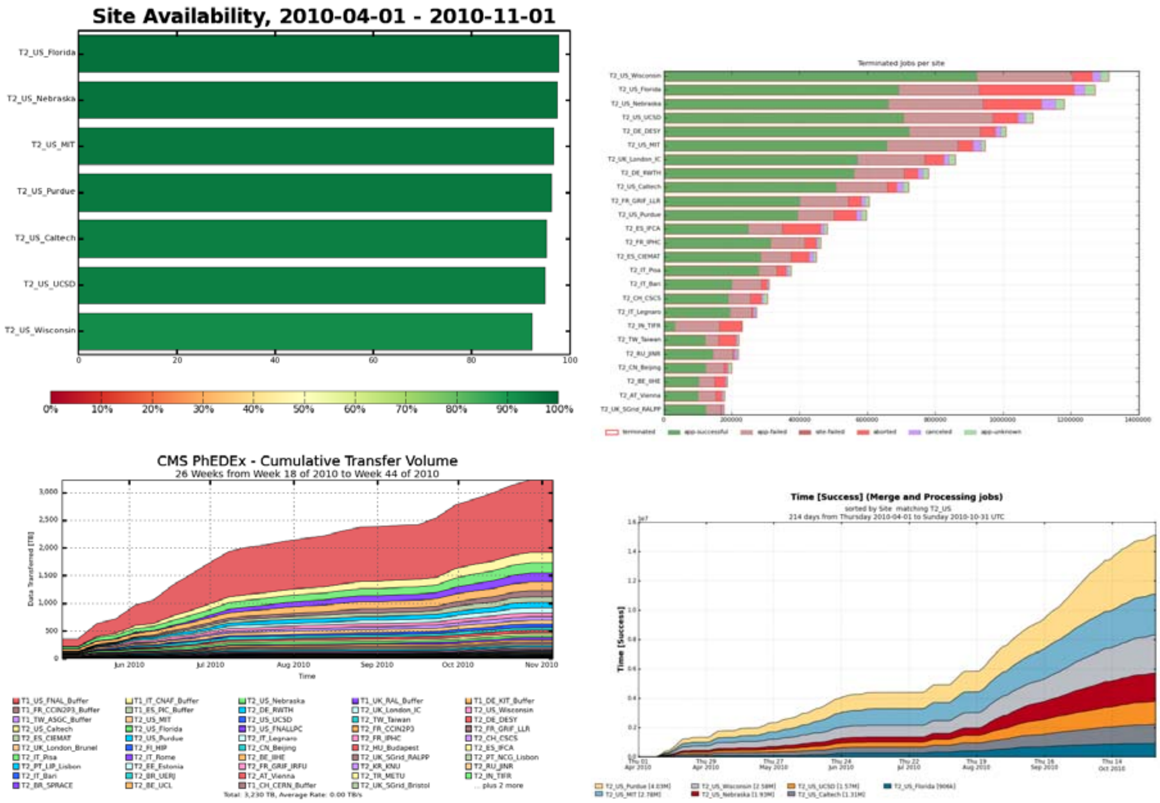

Figure 17: A sampling of U.S. CMS Tier-2 site performance metrics during the 2010 LHC proton run. Clockwise from top left: site availability fraction; number of user analysis jobs at the top 25 CMS Tier-2 sites; amount of time (in hours) contributed to simulation production; volume of inbound data transfers, sorted by site of origin.

computations done at the Tier-2 sites.

The Tier-2s are sufficiently heavily utilized that CMS is already seeing resource contention for processing and storage. Some of this can be addressed by efficiency gains, continual growth in the computing capacity globally, and accessing opportunistic computing at Tier-1 sites, but additional computing for analysis is needed. The Tier-3s are expected to provide additional computing for users to access smaller data collections prepared by the Tier-2 sites. The US has provided 1.25 FTE of full time Tier-3 support effort to help deploy and commission these smaller scale clusters primarily at universities.

In order to facilitate more transparent data access at the Tier-3s and to investigate innovative approaches to data access at the Tier-2s, CMS proposes to collaborate on a research and development facility with the CMS group at Cornell University, in partnership with the Cornell Center for Advanced Computing (CAC). The group will investigate new center designs that could significantly enhanced I/O throughput both locally within the facility and to CERN, Fermilab and other CMS sites. The site would investigate more flexible data caching policies, open data access and more seamless data analysis by use of cloud data services based on Xrootd[21, 22] and similar technologies. The system design will

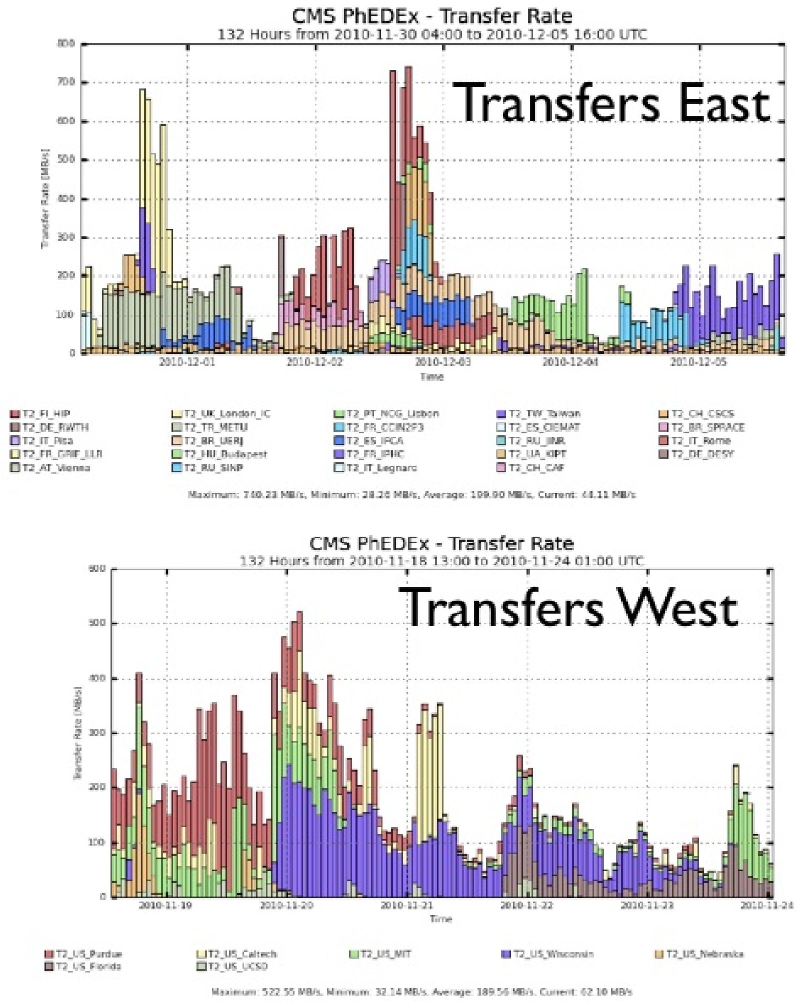

Figure 18: The Transfers from US Tier-2s and FNAL to European Tier-2s are shown at the top. On the bottom are European Tier-1 and Tier-2 transfers to US Tier-2s.

allow researchers to choose a virtual system configuration with flexibility in the requested number of processing cores and the amount of physical memory to be utilized by their task. The new R&D center would collaborate with the the existing CMS effort in this area to try to demonstrate the feasibility of a more flexible center. (See also Section 3.2.2.)

The total scale of U.S. CMS Tier-2 resources is set by the overall needs of CMS computing, the requirement that the U.S. provides its fair share to meet those needs, and the desire to provide U.S. physicists the best opportunity to make discoveries. The overall needs of CMS resources are set by the CMS computing model. This model allows a bottom-up calculation of disk and processing resources based on the anticipated livetime of the LHC, the size of individual real and simulated event records, the CPU time to simulate and reconstruct events, the simulation needs of the experiment and so forth. Now that the LHC is running, we can compare the model's predictions for needed Tier-2 CPU capacity to the actual CPU usage. This is shown in Figure 19. The prediction is adjusted for the actual livetime of the LHC; the changes are modest because much CPU time is devoted to simulations regardless of LHC operations. We see that the model does have reasonable predictive power. If anything, the needed resources seem underestimated.

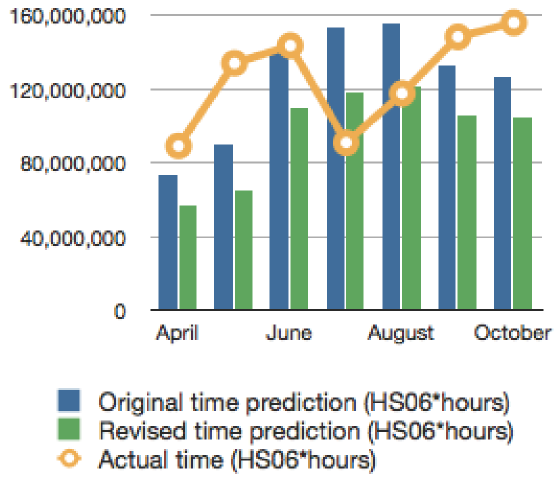

Figure 19: Comparison of Tier 2 CPU usage during the 2010 LHC proton run as predicted by the original CMS computing model (blue), adjusted for actual LHC livetime (green), and the actual usage (yellow).

Each collaborating nation on CMS is expected to provide overall computing resources in proportion to their headcount in the collaboration. U.S. CMS members are about 33% of the collaboration. The US currently provides about 40% of the Tier-1 resources but only about 25% of the Tier-2 resources. This enables smaller nations, who cannot supply Tier-1 resources, to compensate by providing a larger share of Tier-2 resources. However, this could put the experiment at risk if the global Tier-2 infrastructure is not efficiently managed as a balanced system. Moreover, the lack of "nearby" Tier-2 resources could put the U.S. groups, which are among the most active data analysts in CMS, at risk if they cannot get resources from the other Tier-2s reliably.

The pledge that U.S. CMS makes to the WLCG specifies both the CPU and disk resources that are to be provided. The current budget for the U.S. Tier-2 has allowed us to meet the CPU pledge. However, meeting the pledge level for disk has proven more challenging, with many sites struggling to reach it with available funds in any given year. Operating the large disk pools is the biggest technical challenge in the Tier-2 program, and the price of disk has not fallen as quickly as the Moore's Law scaling for processors.

These facts suggest that the current level of funding for the U.S. Tier-2 sites is the minimum that is sustainable to meet the needs of U.S. CMS assuming that we can get appropriate resources from other Tier-2s. Even though the performance of sites has been excellent, they are under-powered in comparison to the needs of the U.S. analysis groups for Tier-2 resources. The most cost-efficient way to deploy more resources is to enlarge the capacity of the seven current sites. After more than five years of effort, there is a tremendous amount of operational expertise at the sites. Just adding hardware at the existing sites would not significantly increase the operational costs. Moreover, operations would not be disrupted to install and commission the additional hardware. In contrast, starting new sites from scratch would mean investing in additional staff rather than devoting those funds solely to computing resources that directly benefit U.S. CMS physicists, and those new staff members would require time to gain expertise at site operations, leading to a delay in the effectiveness of this investment. In this proposal, we are therefore requesting to increase the hardware at each site by amounts varying from 20% to 40% (between $50k and $100k) per year. This will bring our share of Tier-2 resources in line with the US participation in the collaboration. Since these resources will be above our pledged amount, the sites are not obligated to share them with non-US collaborators.

Assuming these changes to the funding profile, the Tier-2 centers will continue to be built to cost, allowing U.S. CMS to meet its current pledges. However, given the uncertainty in the computing model, it is advisable to look for new ways to use existing resources more efficiently. Evolution of the Tier-2 program is being considered in the context of a WLCG-wide re-evaluation of the use of storage systems. One possible new paradigm would take advantage of the reliability of high-bandwidth wide-area networks to stream data directly from storage elements to analysis jobs running somewhere else in the world, removing the current requirement that jobs must be co-located with their input data. This would introduce new flexibility in the computing model, and allow Tier-2 sites to focus mostly on the challenging task of providing large storage systems and leaving the easier task of processing to other sites, such as Tier-3s. Principal investigators from several U.S. CMS Tier-2 sites have submitted a proposal for research and development work on this concept to NSF's Physics at the Information Frontier program.

3.2 Core Software and Physics Applications

CMS software is highly functional, robust, stable, efficient and easy to maintain. U.S. CMS has significant contributions to most development areas. The performance of reconstruction and simulations software was better than predicted, allowing CMS to publish numerous results on detector performance and early physics. There are, however, areas that require further development due to growing demands from running conditions and technology evolution. CMS must ensure that the core framework and infrastructure software is maintained and adapted to changes in computing technology. In the following we give examples of areas where the institutions involved in this proposal will work on further developing the CMS software infrastructure. The NSF funded effort is focused to ensure the success of physics analysis. Together with the DOE- funded work at other U.S. universities, Fermilab, and our international partners, these efforts comprise a coherent software maintenance and development program for CMS.

3.2.1 Multi-core Parallelism

In times past, Moore's law took the form of steadily increasing processor speed. Software would run faster on new platforms with little or no additional programming effort. In recent years, however, advances in semiconductor technology have taken the form of increasing numbers of "cores" (processors) on each CPU chip. CMS software has to be adapted to take full advantage of these gains. The next generation of computing systems will have 48 or more cores sharing memory and I/O controllers on a common motherboard. CMS researchers at Princeton lead this program, which includes strong efforts at Cornell, and other CMS institutions in the US and abroad. Moving CMS software efficiently into the world of massively parallel processes running on multi-core CPUs also requires changes to the job and workload management systems. UCSD is leading this effort in CMS and collaborates in this area with ATLAS and the Condor project.

3.2.2 Data Access and Data Management

In its computing model CMS adopted a simple but successful approach for data placement across the Tier-1, Tier-2 and Tier-3 computing sites. In order to process a data set e.g. for physics analysis the complete data set needs to be transferred to the site. These datasets can be up to tens of Terabytes, putting very high demands on data storage, management and transfer systems. The next generation model realizes the huge potential of very high bandwidth wide-area networks connecting U.S. research institutions. Enabling direct access to individual physics events and sub-events over the wide-area networks eliminates the need for full datasets to be placed at each site. However, it requires a significant evolution of the CMS data management infrastructure, and well thought-through optimizations of data access. Cornell, Nebraska, and Princeton are deeply involved in the Grid storage, data access and application-level data management efforts. They provide leadership and professional manpower for the ongoing development, integration, maintenance and operations efforts and lead the evolution into the next generation data access and data management systems.

3.2.3 User Analysis Job Tracking

The systems for tracking user analysis jobs have been heavily used in the first year. Further development is needed to improve monitoring of user interactions with the distributed systems, both for user job management and data discovery. Researchers and software engineers at UCSD work on analysis job submission and workload-management systems used for analyses running across Tier-2 and Tier-3 sites. Cornell is leading the efforts for data bookkeeping and access and data discovery services in CMS. Both institutions will work on increasing the usability and efficiency of user job tracking.

3.2.4 Event Visualization and Analysis Applications

Visualization tools in CMS are used to inspect interesting events and to carry out checks on reconstruction algorithms by visually examining the results. Researchers and software engineers at UCSD have developed a physics-oriented visualization tool, named Fireworks. The highly successful Fireworks display also plays the important role of providing visual images that help the public understand the research we do.

UCSD will continue to maintain the Fireworks package and to develop and improve the Fireworks display. Work is planned on integrating the display program with the new data access methods that will allow CMS physicists seamless visualization of any event across multi-Petabyte data samples. Fireworks is also being integrated with the analysis framework, thereby allowing full interactive access to any data element or analysis/reconstruction function, and to full geometry information. UCSD and Cornell will also continue work on the analysis framework making it more interactive and increasing its usability.

3.3 Computing Operations

The Operations Program supports several areas in computing operations in global CMS that U.S. CMS takes a leadership role in: software distribution, Monte Carlo production, and Analysis operations. The program also provides support to approximately thirty U.S. CMS Tier-3 computing centers.

Software distribution: CMS maintains a uniform set of CMS software releases across all of the Tier-2 centers worldwide. This work is handled by two installation teams, one for the U.S. and South America, and one for the rest of the world. Tier-3 centers in the U.S. can opt into this service, and many do as it is a great convenience for them. The set of "official" releases are defined by offline release management at CERN. In the U.S., we maintain the capability to install additional releases upon request at some of the Tier-2 or Tier-3 centers, mostly to facilitate development, testing, and debugging of new reconstruction features at significant scale.

Monte Carlo production: U.S. CMS provides the operational leadership for Monte Carlo production worldwide, and the human effort to produce any and all Monte Carlo that is produced at the U.S. Tier-2 centers. Roughly half of all the CMS Monte Carlo in 2010 was produced in the U.S., as mentioned in Section 3.1. The leadership responsibility includes assigning and re-assigning samples to the individual production teams around the world as necessary in order to meet schedule goals.

Analysis Operations: U.S. CMS provides the co-lead for the "Analysis Operations" organization that is responsible for CRAB server operations and user support; management of a 3 PB data cache comprised of 50 TB to 150 TB at each Tier-2 worldwide; and a metrics effort to assess the overall quality of all operational aspects of doing physics analysis in CMS. This data cache hosts all common samples across physics groups for both data and simulation. The initial human effort in all three of these areas was dominated by U.S. CMS. However, as we have scaled up operations with the start of 7 TeV data taking last April, we have added effort from Italy, Germany, the UK, and Belgium, in addition to 1.5 FTE of common CMS operations funded staff at CERN.

Tier-3 Support: In addition to the hardware funded via the present proposal, US-CMS institutions have hardware purchased with a variety of other funds, including university funds, state funds, funds from other programs inside the NSF and at other agencies. While this hardware primarily serves physicists at each host institution, the totality of these resources can provide significant additional capability to the U.S. CMS physics program if fully integrated into the global infrastructure for physics analysis. These clusters are typically operated by physicists who have other responsibilities. The Operations Program supports 1.5 FTE who support the development and operation of Tier-3 sites, 1 FTE of which is funded by NSF. The Tier-3 support team helps them configure their site, integrates the resources into the global infrastructure, operates a central instance of the PhEDEx data-transfer infrastructure for their use, and coordinates community support for the sites. This team is essential for ensuring that physicists get the most physics out of their investments in computation.

Overall, we propose a total of 3.5 FTE to support work in these areas as part of the present proposal. Two of these FTEs—one at Nebraska and another at UCSD—will be funded through this proposal.

4 Detector Maintenance and Operations

In order to maximize the physics impact of CMS, the detector must be operated at peak efficiency with the best possible resolution. This requires constant calibration and monitoring of every component of the detector and its electronics, the trigger and the data acquisition system. Monitoring information must be collected, inspected for problems, and made available to the analysis programs. The detector simulation program must be constantly updated so that the actual performance of the detector at any time during data-takling can be accurately modelled. Vigilant physicists, engineers, and technicians must identify problems quickly, investigate them, and eliminate them or mitigate their effect on the physics,

It will be challenging to maintain the performance of the CMS detector during the 5 year period of this CA. The LHC energy will change from its value of 7 TeV in the center of mass in 2010, possibly to 8 TeV in 2011 and then to 14 TeV in 2014; the luminosity will rise by nearly two orders of magnitude to the design value of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by 2015 and then will increase perhaps by another factor of 2 shortly after 2017. These changes will in turn require changes to the CMS detector, trigger and data acquisition to cope with more interactions in each beam crossing, the onset of radiation damage and aging, and the ever present challenge of maintaining the trigger efficiency.

This is the task of Detector Maintenance and Operations (often referred to as the M&O task). Detector M&O is shared by all nations participating in CMS. In this section, we describe the M&O activities of NSF-supported groups in the current CA and the activities that they plan to carry out during the 5 years covered by this renewal proposal. This is done for each subsystem in which the U.S. has an involvement. The groups whose M&O activities will be suported directly under this renewal proposal are indicated in bold-facce type. In most cases, NSF-supported groups have accepted responsibility for work that grew out of their participation in the NSF-supported CMS Construction Project. However, interests and personnel do change over time so it should be expected that the plan and associations shown below will in fact evolve.

The Detector Maintenance and Operations task, along with its upgrade component, described in section 5, also provides the opportunity for young physicists to learn how the performance of the detector shapes its physics reach and to develop the knowledge, skills and experience that they will need to contribute to detector upgrades and the design of the detectors of the future.

4.1 Hadronic Calorimeter Subsystem (HCAL)

Boston, Brown, Caltech, Fairfield, FIT, **FIU**, FNAL, FSU, Iowa, Maryland, Minnesota, Mississippi, Northwestern, **Notre Dame**, **Princeton**, Rochester, Rockefeller, TTU

In CMS, the hadron calorimeters along with the electromagnetic calorimeters, and muon systems provide combined measurements of jet energies and missing transverse energy. The US was the leader in constructing the hadron calorimeter and provides most of the support to keep it operating. There are four different devices that whose maintenance and operation is undertaken by the U.S.: i) The Barrel Hadron Calorimeter (HB) that is located inside the

CMS solenoid at large radius. It is made of brass plates for the absorber, plastic scintillating tiles with wavelength shifting fibers as the active medium, and Hybrid Photodiodes (HPDs) as the photosensor. ii) The Outer Hadron Calorimeter (HO) is just outside the CMS solenoid. It has the same active medium and photosensor as the HB. Its job is to measure energy leakage out of HB, which happens in very energetic jets. iii) The Endcap Hadron Calorimeters (HE) are located at the ends of the solenoid. The absorber, active medium, and electronics are the same as the for the HB. iv) The Forward Hadron Calorimeter (HF) is outside the iron of the solenoid return yoke in a region of lower field The absorber is steel plates. The active medium quartz fibers that emit Cherenkov light when charge particles, mainly electrons traverse them. The light is recorded with photomultipliers since the field is not high and there is room for magnetic shielding. Quartz fibers are used because they are fast and radiation hard and so can survive and work in the intense radation field in the forward direction. The HB, HO, and HE gives good coverage for $|\eta| < 3$. The HF covers the region from $3 < |\eta| < 5$.

As the major participant in the CMS Hadron Calorimeter system, the U.S. team supplied the absorber and scintillators for the complete barrel calorimeter, as well as the scintillators for the endcap calorimeter and quartz fibers for the forward calorimeters. It also supplied all photo-detectors, all high and low voltage systems, all calibration systems, the complete readout electronics infrastructure and the readout electronics. The U.S. CMS team has been and will remain the major participant in test beam efforts, as well as simulation, software development, and is an important contributor to physics analyses based on the hadron calorimeters.

U.S. CMS retains substantial responsibility for the maintenance and operation of the HCAL. These responsibilities include: calibration and maintenance of all front end and readout electronics; monitoring and maintenance of all photo-detectors; supplying and maintaining the detector control system; creation and maintenance of the databases for HCAL; monitoring and operation of the radioactive source, laser, and LED calibration systems; monitoring of the low and high voltage systems and maintenance of the low voltage system; creation and maintenance of all firmware for detector readout and trigger generation; and data quality monitoring software for online continuous monitoring of the detector.

In recent months, we have focussed on stable operation of the HCAL during 7 TeV colliding beams, in-situ calibration of the HCAL sub-detector using data, and algorithm-filter development to reduce noise background events from the detector. Since the LHC start-up, the HCAL has maintained a very high operational efficiency. This is due in part to the HCAL operations group, which was reorganized with the goal of responding quickly to problems in a way that does not depend on having a large number of people on-site at CERN. The current organization has rotating operations leaders, detector experts, and HCAL shift personnel with varying levels of expertise. The aim for the next run is to improve the HCAL monitoring and alarm system and remove HCAL specific shifts.

The HCAL Detector Performance Group (DPG) worked on filtering of anomalous background events. These noise events come from various sources (photo-sensor problems, RBX coherent noise, etc.) and can be filtered with several algorithms, including timing information and pulse-shape discrimination based on ratios of energy deposition in the second and fourth 25-ns integration time slices. In addition, the DPG worked to refine procedures for calibration. At present, there are enough data collected for ϕ inter-calibration of the forward hadronic calorimeter (HF).

HCAL is planning to replace problematic photo-sensors in HF and the outer hadronic calorimeter (HO) during the next major shutdown (2012 or 2013). In HO, the hybrid photodiodes (HPDs) that are used as photo-detectors exhibit discharge problems when operated in a magnetic field. These problems are worse at fields in the range 0.3 T $< B <$ 3.0 T, the lower end of which is similar to the fields in HO Rings 1 and 2. These discharges mimic high-energy events in the data. Silicon Photomultipliers (SiPMs) have been investigated as replacement photosensors, and test modules using SiPMs have been operated successfully in HO. CMS has accepted the proposal to replace all HPDs in HO (Rings 0, 1, & 2) with Hamamatsu SiPMs during the next major shutdown and production is underway. This project is a collaborative effort between U.S. CMS, India, and Germany (DESY).

In addition to HPD photo-sensor problems, the HF detector also has been shown to be a source of anomalous background events arising from face-plate hits in the readout PMTs. The readout scheme of the HF is based on Cherenkov light from quartz fibers imbedded in an iron matrix. Since the light yield per energy deposition is low, Cherenkov radiation in the face plates mimics large energy depositions. At current luminosities, these hits can be dealt with in software, but the situation will become unacceptable as the LHC approaches its design luminosity. Replacement PMTs will therefore be installed in the next major shutdown. These PMTs, which have thinner windows and metal (rather than glass) envelopes, will be installed in the next major shutdown.

The problem of anomalous signals in the HF has been known and studied in the test beam for several years and has also been characterized in CMS collision data. Although filter algorithms based on isolation and timing/pulse shape have been developed to identify and remove anomalous hits, these algorithms are on the edge of cutting into physics. In current conditions, the algorithms are very effective for isolated spikes, but problems remain with hits overlapping with jets, and pileup. Increasing luminosity, higher center of mass energy, and closer bunches will make the situation unacceptable. For higher trigger thresholds after the shutdown, several of events will have anomalous background signals. Narrow signals due to Cherenkov light from the PMT windows and envelopes are the dominant source of anomalous hits. Replacement PMTs will therefore be installed in the next major shutdown. These PMTs have thinner windows and metal rather than glass envelopes. In addition, four-way segmented anodes provide additional topological rejection of anomalous signals. During the 2012-2016 runs, the multi-anodes will be ganged together into a single readout channel. Upgraded HF electronics being planned for 2016 installation will provide additional readout electronics for the multiple anode PMT signals.

Groups receiving direct support under this Cooperative Agreement are Florida International University (FIU), Notre Dame, and Princeton.

Florida International is responsible for the Detector Controls System (DCS) and the Detector Safety Systems (DSS) monitoring. They have written PVSS based software for setting/reading voltages and currents, and reading out temperatures from the detector. The group commissioned the DCS/DSS sensor hardware and the DSS custom electronics boards.

FIU will continue to support the DCS and DSS systems during the period of this Cooperative Agreement.

Notre Dame developed the Optical Decoder Units (ODUs) and the mechanics for the front-end electronics HB/HE/HO readout boxes and readout modules. These do not require general maintenance. The Notre Dame HCAL group is also a leader in outreach. For example, the ODUs were built by QuarkNet Teachers/Students. Currently, Notre Dame is taking a lead role in the Phase I front-end electronics upgrade, in particular the Silicon PMT sensor development and the mechanics of the electrical/optical layer-to-tower signal summation. ND is also leading the Phase 2 Forward Calorimeter R&D, which involves coordinating the ECAL and HCAL groups to a coherent calorimeter design.

Princeton has been involved in detector operations, HF-based luminosity monitoring, and front-end electronics upgrade development. Detector operations responsibilities include shift coordination and detector expertise. The HF Lumi group will continue to be responsible for the entire HF-based luminosity hardware/software development and the maintenance of that system. The Princeton group is also responsible for interfacing/coordinating with the Trigger Group.

Going Forward: As noted, the U.S. has been the main source for manpower and engineering expertise for HCAL maintenance and operations. HCAL is attempting a new support paradigm to allow other countries to provide support for the detector. The international responsibilities for these projects are still being determined. We nonetheless anticipate that the U.S. will continue to play a major role in HCAL operations.

4.2 Forward Pixel (FPIX) Tracking Detector Subsystem

Colorado, **Cornell**, FNAL, Iowa, **Johns Hopkins**, Mississippi, **Nebraska**, Northwestern, **Princeton**, Puerto Rico, Purdue, Purdue Calumet, Rice, Rochester, **Rutgers**, SUNY-Buffalo, Tennessee, UC Davis, **Vanderbilt**

The U.S. CMS team comprises more than 90% of the group that built the CMS Forward Pixel Detector. The system consists of 16 million pixels, of size 100 μm $\times$ 150 μm, arranged in two disks on each side of the CMS interaction point. Coverage extends from a transverse radius of 6 cm to 15 cm from the beams. Together with the barrel pixel system, FPIX provides high precision measurements of particle tracks nearest the collisions. Because the pixels have low occupancy in spite of proximity to the beam, the pixel detector is the preferred "seed" for the CMS track reconstruction. Because of its excellent position resolution of 15 μm, the pixel detectors are the critical component in the detection of decays displaced from the primary vertex. This is turn provides the ability to identify b-jets and τ-jets, important for discoveries such as supersymmetry or the Higgs boson. The FPIX detector was installed in August 2008 and has achieved high operational efficiency during pp collision running.

FPIX Maintenance: Because this detector is in a very intense radiation field, its performance is expected to degrade gradually and the detector electronics will need continuous adjustment to compensate for this damage as the luminosity rises. We expect that the difficulty and risk associated with performing maintenance in close proximity to the beam pipe will dictate that the detector be removed for maintenance and repair and then reinstalled during each extended shutdown.

Groups in U.S. CMS are the main source of personnel, engineering expertise, and physics knowledge of the FPIX system. This includes calibration and maintenance of all electronics, supply and maintenance of the slow-control and data acquisition systems, continuous adjustment of the system to compensate for radiation damage and varying machine conditions, support of the databases needed to monitor and track performance, support and use of the data quality monitoring (DQM) system, creation and use of the extensive database systems required for, monitoring and adjusting the bias voltage, and calibration of the analog-encoded addressing. Also included will be the extraction of the detector from the IR after each major LHC run and the re-installation before each new run. U.S. groups also play a key role in the beam radiation monitoring (BRM) system, which serves to monitor the radiation levels at the interaction point (IP) and to issue a beam abort signal should those levels rise to the point where the detectors close to the IP are at risk of damage.

The detector will need to be maintained in a cold environment and continuously monitored during each shutdown. The FPIX can only survive about four to five years of operations, based on an assumed luminosity profile, and will then need to be replaced, presumably with a detector based on newer, more radiation-hard technology. CMS has stated that it wants the ability to implement a pixel-tracking trigger at Level 1. This will all require additional research which the US group is uniquely qualified to carry out. The results of the research effort will then need to be used to construct the replacement detector (which is outside the scope of this proposal).

Specific responsibilities of the groups supported under this proposal are as follows:

Cornell is responsible for the DAQ software for the entire pixel detector.

Johns Hopkins plays a leading role in the alignment of the strip and pixel tracker.

Nebraska contributes to the tracker DCS system development and maintenance and its integration with the CMS central DCS. It also contributes to the detector simulation.

Princeton is the leading group working on the luminosity measurements and the operation of the beam radiation monitor (BRM) system.

Purdue provides the key people responsible for pixel operation and the tracker data quality monitoring (DQM). They are also heavily involved in the pixel upgrade.

Rutgers provides electronics expertise. The TBM chip and other chips used in the pixel detector system (e.g. gatekeeper, fan-out) were designed by the Rutgers group. They also maintained the firmware required for the FEC system used by the whole pixel detector.

Vanderbilt provides key personnel for the pixel front end driver readout as well as for the tracker detector controls system.

4.3 Electromagnetic Calorimeter Subsystem (ECAL)

Caltech, Carnegie Mellon, **Cornell**, Florida State, Kansas State, Minnesota, **Notre Dame**, **Princeton**, Virginia

The CMS electromagnetic calorimeter (ECAL) is a hermetic homogeneous calorimeter made of 61,200 lead tungstate ($PbWO_4$) crystals mounted in the central barrel region, closed by 7,324 crystals in each of the two endcaps. A preshower detector is placed in front of the endcaps crystals. Avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps. The US groups in ECAL have specific unique expertise, which makes them crucial contributors. At this point, the US groups have completed construction of their projects and have moved into operation of the ECAL. Overall, US groups contribute to the low voltage power supply system, the laser calibration system and other means of calibration (e.g., using π^0's); the study of long-term radiation damage effects, the development of trigger algorithms, DAQ and DAQ monitoring software; data quality monitoring; alignment studies; the development of shower reconstruction algorithms; ECAL timing studies, and the work to understand and remove the ”spikes” that occur when a neutron hits an APD.

Specific responsibilities of the groups supported under this proposal are listed below.

Cornell: Cornell has been responsible for determining the alignment of ECAL, simulations of the APD response leading to the generation of spikes, other types of noise modeling, and, in general contributions to the ECAL simulation.

Notre Dame: The Notre Dame group has been very active in developing the DAQ and DAQ monitoring software for ECAL. They have also provided trigger expertise in developing the ECAL photon and jet triggers.

Princeton: Princeton has provided DAQ on-line monitoring support and participated in the prompt feedback group that provides fast response information about the data at an early stage.

4.4 Level 1 and Higher Level Triggers

Boston, Brown, **Cornell**, Florida, FNAL, Minnesota, **Notre Dame**, Purdue, Rice, Texas A&M, UC Los Angeles, UC Santa Barbara, **Univ. Illinois Chicago**, Wisconsin

4.4.1 Level-1 Trigger

U.S. CMS groups play major roles in the Level-1 trigger. This system has several components. The Level-1 Regional Calorimeter Trigger (RCT), which detects signatures of electrons/photons, τ-leptons, jets, and missing and total transverse energy in a deadtimeless pipelined architecture that processes 2 Terabits/s of calorimeter data from 40 MHz of crossings with a collision rate of 1 GHz and forwards results to the Global Calorimeter Trigger. The RCT consists of 18 crates containing almost 1300 individual electronics boards. U.S. CMS groups are responsible for the setting and monitoring the HCAL trigger primitives, which are transmitted to the RCT.

U.S. groups are also responsible for the Level-1 CSC trigger for the CMS Endcap Muon system (EMU). The EMU trigger consists of 60 boards operating on the detector feeding optical fibers to a sophisticated track-finder crate that identifies muons from trigger primitives in the cathode strip chambers of the EMU system, measures the transverse momentum in the non-uniform magnetic field and high-rate environment, and forwards these muons to the Level-1 Global Trigger. U.S. responsibilities extend to the creation and transmission of the CSC muon trigger primitives that are provided to the CSC trigger system. Level-1 Trigger Longer Term: The US CMS groups that built the Level-1 muon and calorimeter regional triggers have complete responsibility for their operation and maintenance, as well as calibration. This requires our personnel to be "on-call" during all operations. The group must sustain a major effort to monitor, operate, and evaluate the performance of the trigger electronics on and off the detector. They need to perform daily tests to ensure it is working correctly and is properly calibrated. They maintain and update lists of bad channels (either dead or mis-calibrated) as part of the data quality documentation. They also diagnose and repair trigger electronics modules, cables, power supplies and system components. Since the trigger systems are critical items for CMS, in that we cannot take data without them, the trigger group must provide 24-hour consultation and diagnosis of trigger problems. The group uses a full computer simulation of the calorimeter and endcap muon trigger systems for use in analyses to determine the trigger efficiency. The simulation results are compared to the data and are used to examine *a priori* the effects of proposed trigger adjustments. Changes in the response of the detectors during running will require corresponding changes and updates to this simulation program. The U.S. CMS Trigger group will analyze each data run within one day of its completion using an offline data quality- monitoring program. The operation of the triggers will be compared to reference performance. Additionally, randomly selected events will be processed through the trigger simulation and the simulated trigger results will be compared to the hardware. Any results found out of tolerance will be examined so that problems may be identified and corrected. Finally, the triggers usable for data analysis will be determined for each run.

4.4.2 Higher Level Triggers

The Trigger Studies group (TSG) works on providing higher level triggers and Level-1 triggers tailored for the physics priorities as set by the Physics Coordination. The FNAL, Purdue, UIC, UCSB and Texas A&M groups work on the development and study of new triggers and trigger menus. The Boston, Brown and Minnesota groups work on the trigger menu integration, which involves group integrating and validating the full set of trigger paths that comprise the trigger menu. They evaluate the CPU-performance of the menu ahead of online deployment, by taking into account trigger coincidences and common processing modules for a given L1 bandwidth allocation. The Brown, Cornell, UCSB, Minnesota, Notre Dame and Wisconsin groups work on the trigger performance, which involves evaluating the physics performance of the individual trigger algorithms (physics efficiency of signal events, background rejection and monitoring, both online and offline. This group is also responsible for validating each new software release deployed for use in the HLT.

4.5 Silicon Strip Tracking (SiTrk) Detector

Brown, FNAL, **Kansas**, MIT, Rochester, UC Santa Barbara, UC Riverside, UC San Diego, **Univ. Illinois Chicago**

U.S. CMS institutions played a major role in the construction, commissioning, and operation of the silicon microstrip tracker for the CMS detector. The entire tracker outer barrel (TOB), which comprises 5208 modules and a total of ~3 million micro-strip channels, was produced at two US sites: Fermilab and UC Santa Barbara. In addition, about a half of the modules for the large- radius region of the tracker end caps (TEC) were built there as well. When the construction was completed, the system integration took place at CERN, with U.S. CMS groups providing much-needed expertise and manpower. Significant effort went into commissioning the tracker using cosmic rays during 2008 and 2009, and using LHC data starting in the fall of 2009.

U.S. physicists are now playing major roles in tracker maintenance and in ensuring that the data that is acquired during physics running is of the highest quality. Constant attention is needed to guarantee up-to-date calibration of the system, and to maintain a current list of bad and noisy channels. It is also essential to monitor depletion voltages and dark currents, and to evaluate detector cross talk. Understanding the material distribution within the tracker is crucial for accounting for multiple scattering as well as photon conversions. Alignment improvement is essential for high-quality track reconstruction and efficient identification of b-jets. Optimization of the track reconstruction is vital for efficient analysis across many physics topics. U.S. physicists are playing key roles in all of these activities. Their expertise and experience is essential to continued successful operation of the tracker. Although the device is of high quality, there are still areas of concern, which is not surprising considering that the current system has 10 times more channels compared to the previous largest silicon tracker. Most concerns are related to the cooling system which has leaks. During the next major shutdown in 2012 or 2013, the system will need to be repaired to ensure tracker operation at the low temperatures needed to minimize the radiation damage to the device. The U.S. is planning to play a key role in the silicon cooling system repairs as well as other repair and maintenance work needed by the device.

Specific responsibilities of the groups supported under this proposal are:

Kansas: The focus of the KU effort is the so-called O2O (Online to offline) task. Here, the high voltage and low voltage status for the strip tracker (and now also the pixel detectors) are collected from the online databases and written to the offline database for use in track reconstruction. The mapping of the power supply unit to the detector identification must be checked and a new method was written. KU postdoc Gabriele Benelli is leading this effort since January 2010. Undergraduate students Yasen Ivanov, Alex Porter, and Dave Schudel are working to verify the mapping and the results of the O2O.

Univ. Illinois, Chicago: Members of the UIC group contribute to various tracker activities as detailed below. They include Profs. Cecilia Gerber and Mark Adams, post docs Derek Strom and Victor Bazterra, and graduate students Ioana Anghel and Samvel Khalatian. Strom is resident at CERN and is responsible for DAQ software maintenance and the managing of the online tracker code releases. He has also been trained as tracker shift leader and tracker DAQ on-call. As such he is responsible for the smooth operation of the tracker an average of one week per month per. Two of the more critical items he will be working on in the future are the upgrade to XDAQ10 and the Spy channel noise/pedestal analysis and monitoring. Bazterra continues to support and develop the tracker simulation software. Anghel and Khalatian will continue to take tracker shifts at IP5 and will contribute to data quality monitoring activities.

4.6 Endcap Muon Subsystem (EMU)

Carnegie Mellon, **FIT**, Florida, FNAL, **Northeastern**, Northwestern, Ohio State, Purdue, Rice, Texas A&M,, UC Davis, UCLA, UC Riverside, Wayne State, Wisconsin

The Endcap Muon Subsystem provides muon identification and triggering from $0.9 < |\eta| < 2.4$. It is based on 468 Cathode Strip chambers located on large disks located at either end of the CMS solenoid. U.S. CMS supplied materials, tools, cables and installation hardware for about 400 of these chambers and carried out the assembly, installation and commissioning at CERN. We have an ongoing responsibility for their operation and maintenance. The U.S. team is also responsible for all the readout electronics, including the front end; the peripheral crate electronics, where data are formatted and trigger primitives are created; and the counting-room electronics, where the muon trigger is created and muon data are passed to the central DAQ system. The U.S. CMS team has been and will remain the major participant in simulation, software development, physics object reconstruction, and physics analyses based on the endcap muon chambers. Because of its prominent role in EMU, the U.S. CMS team is the main source for manpower and engineering expertise. Our responsibilities include calibration and maintenance of all front-end and readout electronics and crates; the high-voltage and low-voltage systems, monitoring of gas quality and chamber performance, the detector control system; creation and databases. We also maintain a laser system for the EMU alignment. In addition, the system contains several firmware designs for detector readout and trigger generation, all of which must be maintained by engineers from U.S. CMS. Finally, we anticipate that the upgrade paths for Super-LHC at higher luminosity will require the redesign of the EMU trigger electronics and the completion of the 4^{th} EMU station, work that will be carried out by the U.S. CMS EMU team.

CSC ME1/1 Repair: In order to keep the channel count within the limits of the downstream electronics that existed at the time original the boards were designed, a three-fold ganging was implemented in the cathode strips in ME1/1a. Consequently, each real muon in this region produces one real segment and two indistinguishable ghost segments. This is particularly troublesome for triggering, and thus CMS has run with triggering from these chambers disabled, with no CSC triggers in the region $2.1 < |\eta| < 2.5$. New electronics are being developed to instrument every strip in ME1/1a and to accommodate the increased data rate by replacing copper links with optical links. This repair can be implemented by replacing a few critical boards on the ME1/1a electronics and leaving the rest of the readout and triggering chain intact. During 2010, R&D prototypes were designed and laid out for the new digital cathode front-end board (DCFEB), the optical version of the data mother board (ODMB), and the trigger mother board (TMB).

Northeastern University is the only group receiving support for EMU operations under this proposal. They will be responsible for the maintenance and development of the tools for the transfer, validation, and study of CSC calibration and monitoring constants. Northeastern will also take on the maintenance and development of the CSC module of the CMS visualization code. Northeastern is also beginning to take respopnsibility for the management of ME1/1 repair. Students from Northeastern will provide shift support as well as being active in data quality monitoring.

4.7 The Pixel Luminosity Telescope (PLT)

Princeton, Rutgers, Tennessee, and **Vanderbilt**

To date, the primary luminometer for CMS has been the Forward Hadronic Calorimeter (HF). The HF was selected for this role since it required only minimal additional hardware development and Monte Carlo calculations indicated that the HF would provide good linearity over the range of luminosities expected from the LHC. Performance to date has been consistent with this prediction. There are, however, causes for concern. In particular, the effect of face place hits on the luminosity measurement is hard to model. The plan to refit the HF with PMTs that are less sensitive in this way mitigates this problem, but will complicate the task of luminosity calibration. Moreover, from an operational point of view, we often find that the goals of the luminosity measurement, where stability is prized above all else, come into conflict with the goals of the trigger and physics groups, who also depend on the HF and need to be able to make adjustments to optimize its performance for its primary physics role. These and other reasons motivate the construction of the Pixel Luminosity Telescope (PLT) [25]. The PLT will also provide a real-world test of diamond tracking technology, which is a leading candidate for the extremely hostile environment expected for SLHC.

The PLT provides a relative measure of luminosity by counting the number of tracks emanating from the interaction point (IP). When the LHC is operating at design luminosity, it will determine the luminosity on a bunch-by-bunch basis to a statistical precision of 1% in a time period of less than one second. It uses the standard CMS pixel readout chip (ROC), which greatly reduces the required development effort.

One of the main development items for the PLT is the bump bonding of single-chip diamond detectors to the ROCs. Rutgers and Princeton led a successful bump-bonding effort using the clean room facilities of Princeton's Institute for the Science and Technology of Materials (PRISM). After considerable trial and error, we developed a system that allows us to reliably obtain $>$ 99% bond yields. The left hand side of Fig. 20 shows a detector assembly after bump bonding. Production of the detectors is now over 50% complete.

In May 2009, the CMS PLT group (CERN, Princeton, Rutgers, Tennessee, and Vanderbilt) conducted a highly successful beam test of a prototype three-plane telescope[**??**] (see the right-hand photo in Fig. 20). This test, which was the first demonstration of a diamond-based tracking device, provided a proof of principle of the PLT device. In particular, fast-OR efficiencies of 99.3%, 99.6%, and 99.9% were observed for the three layers in the telescope, respectively.

In light of these promising results, in July 2009 the CMS Management Board (MB),

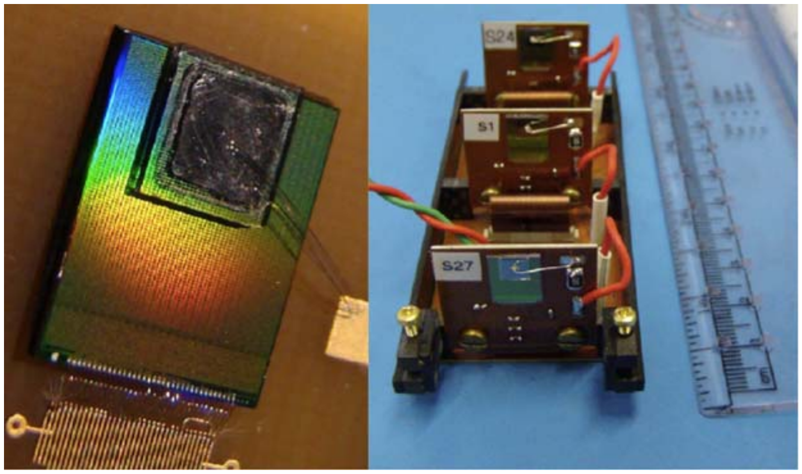

Figure 20: Left: A PLT detector assembly. Right: The three-detector telescope used in the May 2009 beam tests.

endorsed the PLT and recommended that it progress to a “System Test” phase, which culminated in an Engineering and Design Review late in 2009. The outcome of that review was a green light for production of the full PLT. Since then, the efforts of the PLT group have been concentrated on producing the 48 (+12 spares) detector assemblies needed for the complete system and on preparing the readout electronics and software needed to implement a fully autonomous data acquisition chain. This work is on track for a PLT installation at the end of the 2011 run.

5 The CMS Upgrade

5.1 The CERN LHC Upgrade Road Map

In July of 2010, CERN released a technical plan for LHC operations describing the expected luminosity growth over the next two decades. The Phase 1 period started in March of 2010 and extends until 2020. In this period the LHC will achieve its design energy and luminosity. Towards the end of this period, the luminosity should increase beyond the original design value to over $2{\times}10^{34}\mathrm{s}^{-1}\mathrm{cm}^{-2}$. Two long shutdowns, one in 2012/2013 and the other in 2016/2017, will be needed to make the modifications to the LHC to accomplish these objectives. Improvements and upgrades to some CMS sub-detectors will be also necessary to fully exploit the luminosity, especially towards the end of this phase. The two LHC shutdowns provide the access to the CMS collision hall needed to make improvements. Phase 2 will start after 2020, when there will be a third long shutdown for a major machine upgrade to achieve perhaps a factor of 5 higher annual integrated luminosity over that achieved in Phase 1. CMS will also need major transformations to handle the higher luminosity. In particular, CMS will completely replace the tracking detector and will make many other changes to sub-detectors and the trigger and data acquisition systems.

5.2 Physics Justification for the CMS Upgrade

The physics potential of a luminosity upgrade depends on the discoveries of the first few years of physics at the LHC. If the Higgs boson or physics beyond the SM is already discovered, the physics program at higher luminosity will be dedicated to a thorough exploration of the Higgs sector and to measuring the parameters of the new physics as precisely as possible. The higher luminosity will also extend the mass reach for new physics such as multi-TeV particles which appear in many extensions of the SM such as extra gauge-bosons, resonances in extra-dimension models, and heavy SUSY particles. Larger data samples will improve the precision of measurements and perhaps reveal deviations from the SM. For example, measurements of anomalous triple gauge-boson couplings (TGCs) provide a powerful test of the non-Abelian structure of the SM. A tenfold increase in statistics will provide $\approx$ a factor of 3 improvement in precision. It will also yield increased sensitivity to rare processes. For example, the decay of top quarks via flavor changing neutral currents is suppressed in the SM. However some theories beyond the SM predict higher branching ratios for these decays, but often at the limit of LHC sensitivity. This physics program requires CMS to maintain or improve its excellent performance, including low trigger threshold for leptons (μ, e, and τ), b-tagging, and robust measurement of transverse missing energy.

5.3 Description of the Phase 1 Upgrade Plan

The CMS collaboration has outlined its plans for the upgrades to the detector that should be carried out between now and 2016 in the "Technical Proposal for the Upgrade of the CMS Detector through 2020", submitted to the LHCC. Here we summarize the upgrade activities in which NSF supported institutions play a critical role.

5.3.1 HCAL

The upgrade to the hadron calorimeter (HCAL) is directed at handling the increased instantaneous and integrated luminosity, and maintaining robustness and efficiency. This upgrade will include the replacement of the HPDs with a better photodetector, the Silicon Photomultiplier (SiPM), that has recently become available commercially. SiPMs have higher quantum efficiency and gain, and better immunity to magnetic fields than HPDs. Since SiPMs operate at low voltages, they do not experience high voltage breakdown, which produces large pulses that mimic energetic showers, as do the HPDs. These features of the SiPM together with their compact size and relatively low cost allow the implementation of depth segmentation that provides significant advantages in coping with higher luminosities and compensating for radiation damage to the scintillators. Timing information to reduce backgrounds is enabled by the better gain and signal-to-noise ratio of the SiPMs. New back end electronics will enhance the information supplied to the upgraded Regional Calorimeter Trigger. Simulations of the upgraded HCAL indicate that in HB and HE the degradation due to pileup energy deposits can be mitigated by exploiting the longitudinal shower profile in the detector. Separately instrumenting the first layer of the HCAL from the latter ones improves the detector response for e/γ identification.

5.3.2 Forward Pixel Detector

The goal of the Phase 1 upgrade is to replace the present pixel detector with one that maintains high tracking efficiencies at luminosities up to $2{\times}10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The present pixel system was designed for operation with a maximum luminosity of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Severe data losses in the readout chip (ROC) will occur when the luminosity exceeds the design. A replacement of the current system is planned in the shutdown of 2016 before the design luminosity is exceeded. The upgrade consists of

- the development of a new ROC with reduced data loss at the higher collision rates expected by the end of Phase 1;
- the replacement of the current 3-layer barrel (BPIX), 2-disk endcap (FPIX) system with a 4-layer barrel, 3-disk endcap system to provide four pixel hits on eachtrack over the full tracking volume;
- the implementation of ultra-lightweight support with CO_2 cooling and displacement of electronic boards and connections out of the tracking volume for material reduction; and
- the installation and commissioning of a new high bandwidth readout electronics, links, and DC-DC power converters that are required to be able to reuse the existing fibers and cables, which cannot be expanded due to space constraints.

The addition of the fourth barrel layer and the third forward disks will improve the tracking performance in the high occupancy environment of the upgraded LHC. It also provides a safety margin if the first silicon strip layer degrades more rapidly than expected. The upgraded pixel system will have a reduced mass, a smaller inner radius, and increased lever arm providing better tracking, vertexing, and b jet identification.

5.4 Phase 1 R&D Activities and Impact of NSF Support

5.4.1 HCAL Detector Upgrades

Because of its prominent role in the construction of the HCAL detector, the U.S. CMS HCAL team is, by far, the main source of manpower and engineering for operating the current detector. It is natural that the U.S. CMS HCAL group is leading the HCAL upgrade effort.

The key element of the upgrade of the HB/HE is the replacement of the HPDs by SiPMs and the NSF funded groups (Rutgers and Princeton) are leading the R&D effort designed to confirm that candidate SiPMs that meet our requirements will be available commercially on the timescale needed. The issues that are being investigated are: 1) active area; 2) signal/noise; 3) photon detection efficiency; 4) insensitivity to magnetic field; 5) radiation tolerance; 6) linearity of response for single pulse; 7) rate capability; 8) lifetime; 9) temperature sensitivity; and 10) variation in operating voltage at constant gain for an ensemble of parts. A very important part of the R&D is procuring SiPM samples from various vendors for evaluation. Known vendors are Hamamatsu (Japan), FBK (Italy), CPTA (Russia), and Zecotek (Singapore). The NSF groups will purchase larger quantities of promising devices for testing and are prepared to work with the vendors to tailor them to our needs.

The integrated dose of neutrons with E> 100 KeV that will pass through the location of the SiPMs during the lifetime of the SLHC is expected to be about $1 - 3 \times 10^{12}$. Neutrons in this energy range are a problem since they have been shown to induce leakage current in silicon devices. The SiPM must survive these doses with limited degradation. We have started exploring radiation damage to various SiPMs and found that candidate Zecotek devices (MAPD) look very promising.

To incorporate multiple depth segmentation in the calorimeter we will replace the Optical Decoder Unit (ODU) that receives the analog optical signals from fibers which read out each of the scintillating tiles of the calorimeter and optically sums them into towers. We are investigating a new approach that allows us to read out each fiber with a SiPM and then make an analog sum of the electrical output signals of the set of SiPMs (tiles) that would comprise the depth segment of the calorimeter. We believe that this will be both easy to build into the existing system, and would give us maximum flexibility in how we combine the tiles longitudinally. We call this new development the Electrical Decoder Unit (EDU). The optical cables from the calorimeter are plugged into a mating array of SiPMs (linear array) in the EDU. In this implementation we would construct the linear array from individually packaged SiPMs bonded to a substrate. An important part of the proposed R&D is to work with vendors to develop strip array SiPMs that would suitably mate to the analog optical cables from the calorimeter. Options for optical addition are also being explored. The advantage of optical addition is that any given fiber can be used to illuminate an incrementally larger photodetection surface with a correspondingly larger number of SiPM pixels. The total number of SiPM pixels sets the available dynamic range of the SiPM photodetector. This option is particularly important for devices where the feature size limits the pixel density to $\sim$5000 pixels/mm^2. The Princeton and the Notre Dame group will lead the EDU and the ODU R&D respectively.

5.4.2 The Forward Pixel Detector

The U.S. CMS team makes up about 90% of the group that constructed the CMS forward pixel detector. Since the FPIX detector was expected to survive only a few years of operation at the nominal LHC luminosity of 10^{34} cm^{-2} s^{-1}, the U.S. CMS FPIX groups have been already active in R&D for several years. The next few years are critical to bring the project to a construction phase.

Readout chain

The ROC used in the current detector is sufficiently radiation hard to survive the Phase 1 integrated luminosity. However, it will incur rate dependent inefficiencies in the inner regions when the peak instantaneous luminosity exceeds 10^{34} cm^{-2}s^{-1}. To cope with the increased luminosity for Phase 1, the size of the internal data buffers must be doubled. Since we will have more modules than the current detector and the number of optical fibers is limited, we also need to have a faster readout. The redesign of the ROC is the responsibility of the Paul Scherrer Institut (PSI). The changes in the ROC and the readout chain require modifications to the Token Bit Manager (TBM), the device that controls the readout of groups of pixel modules, to accept and produce digital signals. The TBM used in the current detector was designed by the Rutgers group. Rutgers will lead the R&D to revise the TBM to match the changes in the ROC. The modifications that will be needed include replacing the analog switch drivers by digital multiplexers, a Phase Lock Loop (PLL) for clock generation, digital receivers, and line drivers.

Digital signals would travel from the TBM on a new set of extremely low mass, flexible cables to an optical hybrid board, and then along optical fibers to the off-detector data acquisition electronics. The current Analog Opto-Hybrid (AOH) will be replaced with a new Readout Optical Hybrid (ROH) to transmit the data through fibers to the Front End Driver (FED) that sends the pixel data to the data acquisition system. NSF-supported groups (Kansas and University of Illinois at Chicago) are closely collaborating with PSI on the R&D required to fully test the readout chain. The support is complemented by the NSF PIRE and MRI programs. Even though the new ROC is not yet available, the groups are already testing the readout chain using modules with the readout emulation design for FPGA. The test board enables studies of the ROC pulse shape and rise time as a function of irradiation. The studies also aim at fully understanding mechanisms and the development of layouts to reduce the threshold of the ROC. The groups have provided the software and firmware upgrades for running with the testboard and have assembled X-ray teststands at KU and UIC for high rate tests of the readout chain.

Pixel Modules

Each pixel module consists of two rows of 8 readout chips bonded to a pixel sensor. There are 672 identical modules in the upgraded 2×3-disk forward pixel detector, the same number as the current FPIX detector which, however, had 5 different module variants. The single module design will simplify the sensor production, module assembly, and testing. The Purdue group built all the modules for the current FPIX detector. The group is now leading the R&D to automate the pixel module assembly for the upgrade of the FPIX detector. Purdue has already integrated the camera/optics and the vacuum pickup tool to an automated gantry system. The Labview code for pick-and-place of components has been completed and demonstrated to work. The next step is to design and fabricate custom tools needed for prototyping the upgrade pixel module assembly, add a glue dispensing machine and develop software to do pattern recognition. They will share these developments with the group at the University of Nebraska at Lincoln (UNL) which has also recently acquired a similar gantry system with funding from the NSF MRI Program. Purdue and UNL will become the forward pixel module construction centers for the Phase 1 pixel upgrade.

Sensor R&D

For the sensors our baseline is to use the same n^+-on-n technology as for the current detector. The present sensors degrade in two respects with radiation exposure. The signal will gradually decline and one has to compensate by steadily increasing the bias voltage. This leads to a reduction of the Lorentz angle and, therefore, to a degradation of the spatial resolution, which is dominated by charge sharing between neighboring pixels. Second, for fluences exceeding $1 \times 10^{15} N_{eq}/cm^2 (\sim 250 fb^{-1}$ in the inner layer) the signal reduction cannot be avoided and will reach 50%.

The degradation of the spatial resolution could be slowed down if the sensors could be run with sufficient signal at a lower bias voltage. Recent measurements show that sensors processed on mCz Silicon collect the same signal at a lower bias voltage than those processed on the FZ material used for FPIX. An option to get larger signals at a lower bias voltage after high fluences of radiation include the development of non- planar (so called 3D) sensors. The Purdue group is very active in the study of 3D sensors. They have just finished a beam test at FNAL to study the performance of 3D sensors with the current ROC. Several 3D sensors will be irradiated to the doses expected by the end of Phase 1 and Phase 2 at Los Alamos National Laboratory. Beam studies at FNAL to evaluate the performance of the heavily irradiated 3D sensors will take place over the next year. Purdue is also studying samples produced on different wafer types (FZ, mCz, epi) of different thickness and technology (n-in-n and n-in-p with p-stop and p-spray) that will be delivered soon by HPK and Sintef.

Diamond is considered as an alternative material to silicon in high radiation environments, particularly for the innermost layer of BPIX and the inner edge of the FPIX, which, being closest to the beam, suffer the most radiation damage. Rutgers and Princeton are building the CMS Pixel Luminosity Monitor (PLT) which uses diamond sensors and they lead the diamond R&D for the pixel sensors. More radiation hard sensors could help avoid an additional replacement of the inner layers and disks before the end of Phase 1 and are essential for Phase 2.

5.5 Phase 2 R&D for the Phase 2 Tracker Upgrade

When the LHC luminosity increases to well above the nominal design luminosity of 10^{34} cm^{-2}s^{-1}, a substantial upgrade of the CMS Tracking system is needed to cope with the much more demanding requirements and to implement additional functionalities. Operation with instantaneous luminosities of 5×10^{34} cm^{-2}s^{-1} at a rate of 40 MHz, corresponding to approxi-

Figure 21: The tracking trigger concept (left) and an implementation of pixellated p_T modules (right).

mately 100 pileup events per bunch crossing, would result in an integrated luminosity of up to 3000 fb^{-1} after several years of high-luminosity operation. For this phase, the tracking system has to be enhanced in three main aspects: (i) higher radiation resistance, with respect to both instantaneous and integrated luminosity; (ii) higher readout granularity, to keep the channel occupancy at an adequate level; (iii) ability to contribute information for the Level 1 trigger, to help achieve the enhanced discrimination required by the increased pileup.

The contribution of tracking information to the Level-1 trigger is the most novel and challenging aspect of the CMS Tracker Phase 2 upgrade. The trigger system needs to maintain an output rate of 100 kHz despite the 5-fold increase in luminosity, and that appears to be impossible to achieve, using information from calorimeters and muon detectors alone. At present, tracking information is used in the High Level Trigger (HLT), achieving a rate reduction of a factor of ~ 100 in the muon rate. Similar evidence is found for electron, tau, and jet triggers.

Delivering tracking information for the Level-1 trigger involves sending out signals at 40 MHz, which requires data reduction to keep the overall bandwidth at an acceptable level. The strategy that is being pursued in CMS consists in exploiting the strong bending power of the 3.8 T magnetic field to design modules that are able to reject, in real time, signals from low-p_T particles (p_T modules) as shown in Fig. 21. Different implementations of (p_T modules) are under study. Several U.S. CMS groups, including Cornell, are developing p_T pixellated modules which require the use of advanced connection techniques as shown in Fig. 21. The challenge is the connectivity between the two sensors of the stack, which needs to be implemented through an "interposer". The high granularity and the complex connectivity naturally lead to higher mass and power consumption. In the scheme that that is being studyied, there is one layer of ASICs bonded onto a "master sensor" with finer granularity (e.g. $\sim 0.1 \times 1$ mm^2) with analogue connections through an "interposer" to a "slave sensor" with longer channels (e.g. $\sim 0.1 \times 5$ mm^2). Since the electronics is only on one side, the modules can be cooled from the side of the master sensors. The development of these types of modules requires validating the chosen interconnection technologies on large surfaces, and addressing delicate system issues related to the high densities of interleaved analog and digital lines. Such developments require substantial efforts and financial resources.

5.6 Longer Term Outlook

The plan developed for maintaining the performance of the CMS detector as the LHC luminosity increases has been described in great detail in the Technical Proposal that was submitted to the LHCC in November, 2010. We expect the LHCC to recommend CMS to proceed with the detector upgrades planned for the shutdowns which will take place in 2012/13 and 2016/17. To be ready to install detectors, R&D for HCAL and FPIX will have to be completed by 2013 in order to allow the improvements of HCAL and the replacement of FPIX to be ready for installation in 2016. At that point we plan to ramp up the R&D for more radiation hard sensors and the development of p_T pixellated modules for the Phase 2 tracker. Moreover the Phase 2 pixel detector will require the development of a new ROC using CMOS technology of 130 nm or smaller. This will enable the engineering of modules with a smaller pixel size and a ROC with lower readout thresholds. This will result in better spatial resolution and an improved ability to resolve tracks inside high momentum jets, where the present pixel size leads to overlapping hits in jets of energy above 100 GeV. The new ROC should also be able to operate at high efficiency with LHC operating conditions up to $5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is quite clear that upgrade R&D will be an important activity trhoughout the period of the Cooperative Agreement renewal.

6 Common Activities

6.1 Education and Outreach

The U.S. CMS collaboration has a longstanding interest in and commitment to the education of the next generation of scientists and engineers, and in sharing the excitement of our research through public outreach. Our efforts extend over a broad range and involve many of our collaborators who participate at the national and international level, as well as at the local level in the many communities represented by the institutions comprising U.S. CMS.

We participate in formal education (in addition to the classes we teach at our universities) by bringing data to students and developing the tools that allow them to analyze it for themselves. This allows students in the pre-college and early college years to experience some of the thrill of cutting-edge research and highlights the importance of the lessons they learn in class. In these efforts we collaborate with other (NSF sponsored) groups, primarily QuarkNet and the I2U2 Collaboration (U.S. CMS collaborators were founding members of both of these programs). These groups bring substantial expertise in reaching students and teaching at the secondary level. Each year we reach hundreds of high school science teachers.through these programs,

U.S. CMS collaborators are actively involved in many areas of informal education. Many of our members sponsor undergraduate college students to join them in their research. Undergraduates are working on many aspects of the LHC program, from the physics we are doing to researching interesting detectors and materials for the upgrade. For more than a decade, we have sponsored the U.S. CMS Fellowship Program. Each summer U.S. CMS sponsors six to eight high school teachers to join in the research program with a U.S. CMS scientist. These fellows gain valuable experience, which they can then take back to their classrooms, and they make important contributions to the CMS research program.

We also participate in various forms of outreach to the general public. The LHC and its detectors are technological marvels, with which we endeavor to answer some of the deep questions of physics. Our research program is thus of interest to a large segment of the public, who are deeply curious about the science we are doing. Our collaborators have written books, numerous articles in newspapers and magazines, and have given public lectures highlighting the machine and the research program at CMS. We have developed particle detectors for museums that highlight our field, and hand-held particle detectors for use in public lectures. We have been at the forefront in developing materials—including videos, brochures, and tools for data visualization.

The funds needed to support these activities have been supplied through the current Cooperative Agreement. They are used to support students and teachers when they participate in the programs and activities described above; to provide travel for U.S. CMS Outreach personnel to outreach meetings; to purchase computer equipment; and to buy materials to put together demonstrations. Currently, funding for E&O is about $200K. We plan to keep it at that level under the new CA.

6.1.1 Outreach

U.S. CMS is an active participant in the LHC Awareness Program (along with members of the U.S. ATLAS outreach group). The flagship endeavor of this group is the development of an animated video that highlights some of the significant outstanding questions in the field of particle physics. The viewer will then “ride along” with the main character to CERN, where we are trying to answer these very questions.

The U.S. CMS collaboration, through its Education and Outreach group, contributed to the development of a CMS movie, which has been available for several years now. U.S. CMS scientists participated on camera and many contributed ideas to the movie. We have also worked with the international collaboration toward the development of a CMS brochure highlighting the physics program, and the development of the CERN playing-card decks for the 50$^{\text{th}}$ anniversary of the laboratory. These cards continue to be quite popular and we place large orders for these card decks to provide our collaborators with handouts that people keep and use. U.S. CMS has been sponsoring a small group of high school physics teachers and their students for the past several summers to develop a Digital Video Theater presentation of the LHC and main experiments. This past summer, the group completed the model of the accelerator and all four detectors—CMS, ATLAS, LHCb, and ALICE. We continue to work on a method of reading event data into the model so that we may display events in “real time” during a show. This model can be controlled by the theater operator and “flown through” to give a sense of scale. This effort will culminate in a package which is suitable for display in planetarium shows and digital theaters worldwide. Since the patrons at planetaria are necessarily interested in science, this is a natural audience for us and we are excited about the possibilities. In this effort we have collaborated with professionals at the Adler Planetarium (in Chicago) and the Jordan Hall of Science Digital Video Theater (at the University of Notre Dame). The model that the group has created has already been used by several professors at Notre Dame during their lectures, and during a public lecture there. During the startup of the LHC in March 2010, the public relations office at Fermilab organized a nationwide series of lectures by physicists to to take advantage of the unique opportunity presented by the attention that CERN was commanding. U.S. CMS and U. S. ATLAS both supported this effort, and many of our collaborators participated in public lectures at their home institutions. Many of us also held public events to watch the accelerator status as the LHC began operations again in the spring of this year. Despite the ungodly hour in the U.S. at which the machine startup occurred, these events were well attended. The web tracking statistics from CERN during the startup show hundreds of thousands of hits to the CERN web pages from unique IP addresses.

As the LHC came online over the summer, we began an “Event of the Week” project. Interesting events from one of the experiments are posted on a public website, along with a short description of the event and why it is of interest. The events are provided by the experiments, and are hosted by QuarkNet. U.S. CMS collaborators provide advice and insight to the QuarkNet staff, who maintain the event displays and write the captions. It is still too early to tell what impact this might be having, though the web pages are garnering significant traffic.

6.1.2 Education

U.S. CMS is deeply committed to educating the next generation of scientists and engineers. We are full participants in groups dedicated to improving science education in our high schools, to developing science teachers nation-wide, and to providing data and analysis tools to students. We have also launched informal educational efforts at museums and in our home institutions.

Formal Education U.S. CMS collaborates with the NSF-sponsored programs QuarkNet and Interactions In Understanding the Universe (I2U2). We were founding members of both programs, and several of our collaborators (along with representatives from U.S. ATLAS) continue to serve as principal investigators of both programs, and on their advisory boards. Through these collaborations we make significant contributions to the professional development of science teachers throughout the nation's high schools, and aid in the creation and dissemination of data-driven classroom activities throughout the nation and the world. The QuarkNet program (`http://quarknet.fnal.gov/`), now in its twelfth year, is a professional development program for teachers of secondary science. The collaboration has over 50 centers nationwide, where local university and laboratory groups interact with science teachers in their communities. Approximately half of these groups are institutions which are part of the U.S. CMS collaboration (and approximately half are members of the U.S. ATLAS collaboration). A small number are primarily focused on the D0 and CDF experiments at Fermilab. Teachers partner with scientists and contribute to the research they are engaged in. Many centers also host a summer research program, which includes the teachers and high school students. Through our widespread collaboration with QuarkNet, U.S. CMS reaches hundreds of secondary science teachers directly, and many hundreds of students indirectly, making significant contributions to the scientific literacy of the next generation.

The I2U2 collaboration (`http://www.i2u2.org/`) is a group that is charged with investigating the potential of data-driven electronic laboratory work in the classroom (known as an e-Lab). Through the efforts of several of U.S. CMS collaborators, the CMS experiment has committed to providing a subset of our data for use in formal education and outreach activities. The infrastructure and analysis tools have been developed in collaboration between U.S, CMS and I2U2. The CMS Test Beam e-Lab (begun in 2003 and using data from a 2004 test beam at CERN) was a pilot project where U.S. CMS developers explored the design of a data analysis tool without encountering the complexity of analyzing a full collider event. As collider data has become available and the data formats were understood, additional work was done to explore the differences necessary to analyze live data from CMS.

Beginning in Fall 2008, the U.S. CMS team investigated the differences in data selection that would be necessary as they moved from a test beam based e-Lab to an e-Lab based on CMS data. This work was completed (on the CMS side) late in 2009.

This year I2U2 is rolling out an e-Lab based on LHC early run data. An activity to identify candidate Z-decay events familiarizes students with CMS single-event displays. The new e-Lab also includes an innovative 3-D event display. With the improvement in libraries available to web developers and the faster speeds of processors, I2U2 computer scientists showed that it is possible to have a browser-based 3-D event display that mimics standard

Figure 22: Quarknet participants took on the construction of optical readout modules for the CMS hadronic calorimeter readout.

CMS tools like Fireworks, a standalone package developed by CMS physicists for use in the experiment. With the tools developed by U.S. CMS scientists and I2U2 computer scientists, students are able to analyze particle physics data individually and in bulk, in ways very similar to what we do on the experiment. This is an innovative program which holds great potential for educating students with data-driven cutting-edge research.

U.S, CMS, working closely with I2U2 and QuarkNet, has taken the lead in the development of the CMS Masterclass. The on-line event display was created by I2U2 we have obtained J/ψ data to start the analysis project under the auspices of QuarkNet and I2U2. Guided by CMS physicists, QuarkNet teachers worked to create and test a data analysis exercise and supporting materials using the event display.

In Masterclasses 2011, students will look at sets of candidate J/Ψ dimuon events. They will evaluate the quality of the muon tracks and eliminate any same-charge pairs to attempt to create a set of criteria for finding the most likely J/ψ candidates. They will create mass plots from selected events to check the application of their criteria. Students will compare mass plots and selection criteria in their Masterclass Institutes and then again in video conferences. Work continues on W/Z exercises as well, albeit at a lower priority. The test website for the CMS Masterclass is currently on-line at

`http://leptoquark.hep.nd.edu/kcecire/mc/cms.html`

. We are currently working to translate the site into multiple languages for use world-wide.

Informal Education U.S. CMS also makes a significant effort in the area of informal education. These are activities which educate and inform both students and the public without necessarily involving a classroom setting. We have developed demonstration cosmic ray detectors for museums. One of these shows a visual track of cosmic ray muons in real-time and is currently in the National Air & Space Museum. Another, the Cosmic Ray informal Laboratory (CRiL) has several incarnations. The original is currently in use at the Adler Planetarium in Chicago. Another is on display at CERN. A third is being developed into a remotely controlled detector so that interested high school science teachers may collect their own data with their students at their own schools. Several U.S. CMS groups have built their own versions of this detector (notably the group in Miami, which resulted in a nice article in the Miami Herald about the collaboration between U.S. CMS scientists and high school teachers and students). During National Lab Day this past spring, U.S. CMS scientists carried one of these small detectors to the National Air & Space Museum in Washington, D.C.. We spent two days demonstrating a particle detector to museum patrons and collaborating with high school teams from QuarkNet in gathering data during the event for later analysis.

U.S. CMS scientists, collectively and individually, are committed to providing a rich environment for the inclusion of undergraduate college students to be full participants in our research. Students have been involved in the design, construction, commissioning, monitoring, computing infrastructure, and data analysis. Most U.S. CMS institutions have at least one undergraduate student working with their group and several have over 10 students per year. Students typically work at their home institution during the academic year and many then travel to Fermilab or CERN during the summer to continue the research. Some of this research has been supported through the funding from the U.S. CMS project including travel expenses and hourly wages. For example, for the tracking project, there are over 2000 power supplies which need to be monitored. Undergraduate students supervised by postdoctoral researchers located at CERN have helped to provide the software framework and map the cable paths for the entire system. Their stay during the summer at CERN where they have interacted with students from all over the world has provided them a sound basis for their entry into graduate school. Students have also been supported through enhanced NSF REU and Partnerships in International Research and Education (PIRE) programs. For the PIRE program, about 10 students from five U.S. institutions (Univ. of Kansas, Kansas State Univ., Univ. of Nebraska at Lincoln, Univ. of Illinois Chicago, and the Univ. of Puerto Rico at Mayaguez) travel to the Paul Scherrer Institute (PSI) near Zurich and also to ETH Zurich to take courses. The research topics are diverse and include physics analysis; however the focus has been on preparing for the Phase 1 pixel detector upgrade. U.S. CMS funding has helped to support the two postdoctoral researchers who are resident at PSI who help to manage the student research projects. The PIRE grant will sunset after 2012. While continuing the scope of the entire program is not feasible here, we propose to continue to provide up to 5 grants for instrumentation work. With the framework and experienced personnel already in place, these students would travel to Switzerland for two months and focus on research for the pixel detector upgrade.

Figure 23: Students, faculty, and research staff associated with the PIRE program on site at the Paul Scherrer Institute.

U.S. CMS Fellowships have been an annual summer program of the collaboration for over a decade. These fellowships devote $6,000 each to a U.S. CMS physicist to support a high school teacher for a summer while they participate in the CMS research program. We typically support 6-8 teachers each summer, making this program the single largest budget item for E&O in U.S. CMS. The teachers involved have worked on test beams, installation, and calibration at CERN. Conducted research in bringing the CMS scientific program into the classroom, investigated new materials for use in CMS detector elements, and conducted research and development for the CMS upgrade which is still many years down the road. These teachers have not only gained valuable experience which they can take back to their classrooms, they have made positive and important contributions to the CMS experiment.

U.S. CMS has also, for the past several years, contributed to an innovative program at the University of Rochester aimed at encouraging young (middle school to early high school) girls in the sciences. This program has been quite popular, and U.S. CMS scientists participate and use examples from CMS during the program.

PIRE One important aspect of the education program the engagement of undergraduates in CMS research. Undergraduates have been involved in the design, construction, commissioning, monitoring, computing infrastructure, and data analysis. Most US universities involved in CMS have had at least one undergraduate student working with them. Cornell, Kansas, MIT, UC San Diego, Caltech, and Florida have engaged over 10 students per year.

Students typically work at their home institution during the academic year and many then travel to Fermilab or CERN during the summer to perform their research.

The Operations Program has successfully engaged undergraduates in technical work and has provided funds for hourly wages and travel. A typical example was a small project to develop a system to monitor the 2000 power supplies in the tracker system. Undergraduate students supervised by postdoctoral researchers located at CERN helped to provide the software framework and map the cable paths for the entire system. The time they spent at CERN over the summer gave the students an opportunity to interact with students from all over the world and has provided a sound basis for their entry into graduate school.

Students have also been supported through enhanced NSF REU and Partnerships in International Research and Education (PIRE) programs. For the PIRE program, about 10 students from five U.S. institutions (Kansas, Kansas State, Nebraska at Lincoln, Illinois at Chicago, and Puerto Rico at Mayaguez) travel to the Paul Scherrer Institute (PSI) near Zurich and also to ETH Zurich to take courses. The research topics are diverse and include physics analysis, however the focus has been on preparing for the Phase I pixel detector upgrade. Though the bulk of the funding for this work came through a separate PIRE grant, the U.S. CMS Operations program provided funding to support two postdoctoral researchers who are resident at PSI who help to manage the student research projects.

6.1.3 Going Forward

A scientifically literate populace is essential to the future well being of the U.S. Moreover, we believe that our work is not complete until we have shared its fruits as widely as possible. To that end, we are committed to continuing the Education and Outreach activities described above. Although the basic form of this effort will remain the same, it will change in detail as CMS moves from the early phases of operation and begins to realize the full discovery potential that will accompany the acquisition of large data samples.

We believe that the best outreach efforts are begun at the local level, with U.S. CMS collaborators targeting their own communities. We intend to expand our support for these local efforts and collect the experiences of our collaborators so that their innovations may be disseminated throughout the collaboration and others are informed and inspired to innovate in their own local area. We will also continue with our international efforts, particularly to the extent that they foster an understanding between U.S. students and their counterparts abroad, such as when undergraduates receive support to spend time at CERN and the institutes of other foreign collaborators.

6.2 Common Fund Contributions to the Operation of CMS

The CMS collaboration is a very large organization whose job it is to maintain and operate CMS so as to produce the best possible physics. CERN has a very specific set of rules on how experiments support their activities. These rules are captured in various Memoranda of Understanding as well as a document called the "General Conditions Applicable to Experiments at CERN."

6.2.1 M&O Category A

Budgets for the support of common CMS activiites—i.e., those that are not the responsibility of any one nation or institute—are called "M&O Category A" funds. These budgets are produced by the CMS collaboration Finance Board in consultation with all parts of CMS and approved by the CMS Management Board and the CMS Collaboration Board. They are submitted for approval to the Resources Review Board (RRB) that reports to the CERN Director of Research. Budget proposals are carefully examined by a "Scrutiny Group (SG)" to make sure that they are adequate for the experiment's operation, but do not place an excessive burden on CMS's collaborating national funding agencies or institutions by the inclusion of non-essential items. The U.S. NSF and DOE suggest members for the SG. The DOE and NSF also have representatives on the RRB that are present for the discussion of the annual budget that usually occurs in October of each year. Once the RRB approves the budget, the CMS Resources Manager invoices each funding agency or institute based on the fraction of PhD physicists it has in CMS. For NSF, this is the fraction of PhD physicists in insitutions having NSF core program support. This is typically about 6-7% of all of CMS and about 20% of all U.S. PhDs. This fee varies from year to year but has stabilized at about 5MChF for the U.S.; NSF's pro rata share is about 1 MChF. (at this time, $1 $\approx$ 1ChF.) The U.S. CMS Operations Program pays this fee for U.S. Ph.D. participants. Typically, we pay in two lump sums, one for NSF and one for DOE. The optimal timing of these payments depends on many factors and varies from year to year.

6.2.2 M&O Category B

The support of individual subdetectors (for example, ECAL or HCAL), is the responsibility of the institutes that built them. The associated funds are called "M&O Category B" funds.

CMS requires all physicists to be affiliated with some aspect of detector maintenance. Each subdetector prepares an annual budget and assessments are made to institutes based on the fraction of PhD physicists of that institute that are in the subdetector. The budget is then reported to the CMS Finance Board which scrutizes the budget and recommends it to the Management Board for approval. The funds for the NSF institutes are embedded in the U.S. Operations Program subdetector budgets and are supplied through the grant subawards to individual institutions.

6.3 Princeton Project Office

This proposal encompasses 16 subawards and thus involves a significant amount of administrative work. A modest program office will be established at Princeton to handle this administrative load. Based on experience with the previous award, which was hosted at UCLA, we will need one full time administrator who is familair with university grant procedures and also the procedures of the U.S. CMS Program. The person will serve as liaison between Princeton's Office of Research Projects Administration(ORPA) and the U.S. CMS Program Office at FNAL, and will deal with counterparts in the universities receiving subawards. Specific duties will include: i) collecting and filing Statements of Work (SOWs) and, if necessary, revised 1030 budget forms at the beginning of each funding year; ii) working with Princeton's ORPA to ensure that subawards are issued/amended each year; iii) receiving and checking invoices submitted by subawardee institutions; iv) maintaining financial tracking information to be provided to the NSF in interim and annual reports. This person will also be responsible for ensuring that NSF policies as well as those of Princeton and U.S. CMS are followed in a consistent manner.

During the current award period, the PI developed a web-based document management system using the web programming language PHP. This system, which comprises a MYSQL database and a set of web pages, will be carried over to this award. It allows the program office personnel, the U.S. CMS subsystem managers, and the PIs to upload and examine documents associated with the program (e.g. SOWs, budget sheets, subaward documents, and invoices). The PHP system also incorporates functions that allow one to keep track of various processes. For example, when an invoice from a subawardee is first received at the program office, it is uploaded and a database entry is created to track the steps involved in its approval and payment. As each step is completed, the database is updated. The PHP interface then allows authorized individuals anywhere in the world (important given the dispersed nature of U.S. CMS) to check on the status of the invoice.

7 Budget Overview

Table 3 provides an overview of the budget for the first year of requested funding (~FY12) broken down by functional area and institution. Budgets for the out years are quite similar. Additional details can be found in attached 1030 budget sheets and also in the accompanying budget justification documents. The total requested annual budget is $10M per year.

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Table 3: Breakdown of funding by institution and budget category for Year 1 (FY12) of this request.

Institute	Total	Detector M&O	Tier 2	S&C	Common Operations	Upgrade R&D
Caltech	$607,650		$607,650			
Cornell	$610,280	$12,720		$339,560	$135,000	$123,000
Florida	$592,050		$592,050			
Florida Intnl.	$50,922	$50,922				
Illinois Chicago	$80,552	$52,668				$27,884
Johns Hopkins	$28,720	$28,720				
Kansas	$129,347	$18,720			$87,800	$22,827
MIT	$644,050		$644,050			
Nebraska	$1,036,205	$36,449	$627,590	$217,360	$120,400	$34,406
Northeastern	$25,680	$25,680				
Notre Dame	$613,403	$87,651			$112,201	$413,550
Purdue	$1,086,376	$125,436	$603,490			$357,450
Rutgers	$129,906	$93,906				$36,000
UC San Diego	$1,311,335		$607,650	$703,685		
Vanderbilt	$172,120	$114,070		$20,800		$37,250
Wisconsin	$549,410		$549,410			
Princeton	$2,331,993	$139,800		$444,684	$1,556,739	$190,770
Total	**$10,000,000**	**$786,743**	**$4,231,890**	**$1,726,089**	**$2,012,140**	**$1,243,137**

Funding for the previous five-year cooperative agreement award was $9M/year. This request therefore represents an annualized increase of 2.1% over the previous five-year CA, which is somewhat below inflation. Roughly 88% of the requested funding—i.e., all but the upgrade R&D—represents a continuation of activities that have been ongoing for quite some time and reached a steady state when CMS began regular detector operations in 2008 (we ran on cosmic rays for a long time before the LHC delivered collisions). The corresponding costs are well understood. While it is difficult to predict the cost of upgrade R&D with as much certainty, the amount requested is commensurate with the number of NSF groups in U.S. CMS—i.e., about 25-30% of the total amount that we allocate to upgrade R&D.

Detector M&O covers the costs associated with running CMS and keeping it in tip-top shape for data taking. Tier-2 costs cover salaries for two FTE's at each Tier 2 site plus an annual expenditure in the $250K-$350K per site range for new and replacement hardware. S&C costs cover the salaries of software professionals, some of whom are involved in data operations and others of whom are responsible for software development. Common Operations includes such things as Education and Outreach (Notre Dame); a postdoc based at the Paul Scherrer Institute in Switzerland to supervise students in the highly successful PIRE program (Kansas); a general support person to help physicists with CMS software and computing issues (Nebraska). The Princeton portion of the Common Operations costs includes the annual Category A common fund payment (estimated to be \$985K in 2012) and the cost of operating the Princeton program office. In FY12, there is a one-time cost of \$244K associated with the cost of initiating the 16 sub-awards, in keeping with the standard practice wherein the host institution applies indirect charges to the first \$25K of each sub-award.

Note that some institutions participating in this proposal will also receive program support from the DOE. In particular, the Tier 2 institutions receiving core-program support from the DOE will generally receive support for their non-Tier-2 detector M&O and S&C activities through DOE program funds.

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