Final Report for DE-FG02-07ER41465
High Energy Physics Research with the CMS Experiment at CERN
University of California, Riverside

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1. Introduction and Overview

The highlight of our last budget period, June 1, 2010, to May 31, 2013, was the discovery of the Higgs boson by the ATLAS and CMS experiments [1, 2] at the CERN Large Hadron Collider (LHC), announced on July 4, 2012, and for which François Englert and Peter Higgs were awarded the 2013 Nobel Prize in Physics on October 8, 2013. The Higgs boson was postulated in 1964 [3-5] to explain how elementary particles obtain mass and was the missing piece of the Standard Model. However, the Standard Model does not describe everything that we know. There are many unanswered questions, such as how can the Higgs boson have the mass that we have observed, are there more Higgs bosons, why is there more matter than antimatter, and what is the invisible dark matter, which constitutes about 85% of the matter in the universe. Our group played a significant role in the discovery of the Higgs boson and in subsequent analyses. We also carried out searches for new physics, in ways that could help elucidate some of the remaining questions. Our role in the CMS detector focused on the Tracker, a silicon strip outer tracker and pixel inner tracker.

The members of our group during the grant period are listed below:

Teaching Faculty: Gail G. Hanson, Distinguished Professor (PI).

Postdoctoral Researchers: Gabriella Pásztor (unpaid), Asish Satpathy (unpaid), Mauro Dinardo, and Martina Malberti. The first two postdoctoral researchers had to be let go in 2007 because the grant did not make up for Hanson's startup funds nor for the reduction in DOE funding imposed by the final PI at Indiana University, where Hanson was a Distinguished Professor and previously overall PI of the grant.

Graduate Students: Geng-Yuan Jeng, Hongliang Liu, Robert Stringer, Xu Xu, Kira Burt, and Manuel Olmedo. Jeng, Liu, and Stringer finished their PhDs in 2011, and Xu left the graduate program at the beginning of Fall 2012.

Undergraduate Student: Manatosh ("Milton") Bose (2008-2009).

2. Physics Analysis

2.1. Discovery of the Standard Model Higgs Boson

The principal discovery channels [1] for the Higgs boson (H) were $H \to \gamma\gamma$, $H \to ZZ \to 4\ \ell$ (ℓ = e or μ), and $H \to W^+W^- \to \ell^+\ell^-$ plus missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). The first two channels have the best mass resolution, whereas $H \to W^+W^-$ shows a broad excess.

Hanson has been working on searches for the Higgs boson, both standard model and beyond the standard model, for many years, particularly in the OPAL experiment at LEP before CMS. She was invited to write a review of Higgs searches in 2009, just before LHC data taking began [6]. She and Liu developed the tracker-seeded photon conversion producer to help improve the photon-photon mass resolution in $H \to \gamma\gamma$ in two ways: better resolution of the

vertex for those Higgs decays in which at least one photon converts to an e^+e^- pair in the rather large amount of material in the tracker [7] and better understanding of the material in the tracker in front of the electromagnetic calorimeter [8]. Xu joined the $H \rightarrow \gamma\gamma$ group in 2011 but was replaced by Olmedo in late 2012. Malberti, an expert on the $H \rightarrow \gamma\gamma$ analysis and the electromagnetic calorimeter, joined U.C. Riverside in May 2013.

The first Higgs $\rightarrow \gamma\gamma$ results were shown at the EPS and Lepton-Photon conferences in the summer of 2011 [9]. The 4.8 fb^{-1} of 7 TeV data taken in 2011 showed an excess near 124 GeV in the Higgs $\rightarrow \gamma\gamma$ channel with a local significance of 3.1 σ, as presented at CERN on December 13, 2011, and published in early 2012 [10].

The 5.3 fb^{-1} of data accumulated at 8 TeV by June 2012 were combined with 5.1 fb^{-1} taken at 7 TeV in 2011 and were presented at a special seminar at CERN on July 4, 2012, and at the ICHEP conference. These data showed an excess at 4.1 σ local significance at a mass of about 125 GeV in the Higgs $\rightarrow \gamma\gamma$ channel alone [11]. When combined with the searches in the ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$ channels, the local significance is 5.0 σ [12]. A fit to the two channels with the best mass resolution, $\gamma\gamma$ and ZZ, gave a mass of 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. Figure 1 (a) shows the observed local p-value for 7 TeV and 8 TeV data for the $\gamma\gamma$ decay mode, and their combination, and Fig. 1 (b) shows the data, the signal model, and the background model for the $\gamma\gamma$ decay mode, all weighted by a weight proportional to $S/(S + B)$. Figure 2 shows a scan of the local p-value for the combination of the five decay modes for the 7 and 8 TeV data sets and their combination. This observation paper has been published in *Phys. Lett.* ***B*** [1].

Further improvements continue to be made in the analysis, in particular Multi-Variate-Analysis (MVA) techniques, and the full 19.6 fb^{-1} of 8 TeV data were included. Preliminary results using the full data set were shown at the Moriond Conference in March 2013 [13], and the final publication is in preparation.

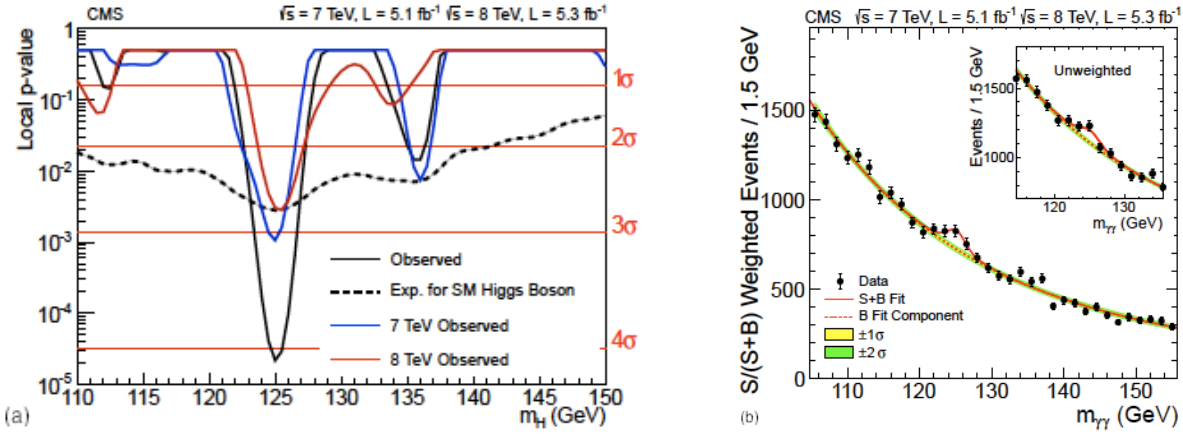

Figure 1: (a) The local p-value as a function of m_H in the $\gamma\gamma$ decay mode for the combined 7 and 8 TeV data sets. The additional lines show the values for the two data sets taken individually. The dashed line shows the expected local p-value for the combined data sets, should a SM Higgs boson exist with mass m_H. (b) The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ of its category. The lines represent the fitted background and signal, and the colored bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution (from Ref. 1).

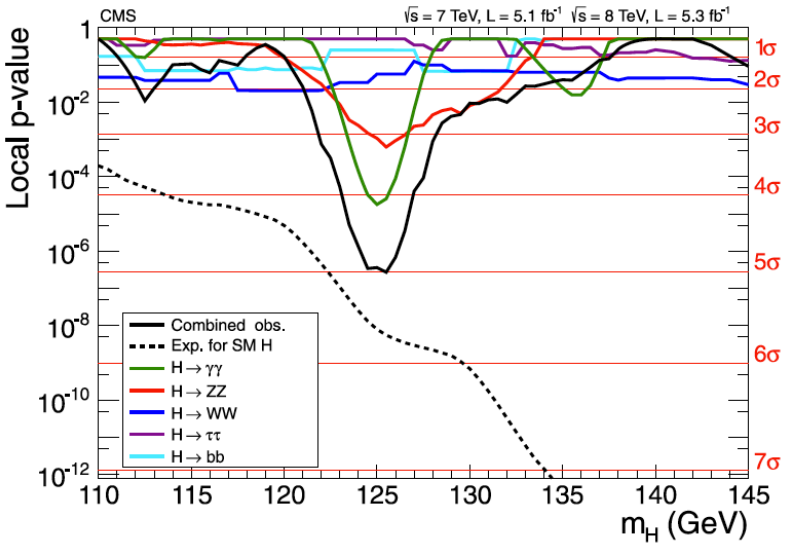

Figure 2: The observed local *p*-value for the five decay modes for 7 TeV and 8 TeV data, and their combination as a function of the SM Higgs boson mass. The dashed line shows the expected *p*-value for a SM Higgs boson with mass m_H (from Ref. 1).

2.2. Searches for New Physics

2.2.1. Searches for Supersymmetry (SUSY) and Universal Extra Dimensions in Events with Photons and Missing Transverse Energy. Hanson and Stringer have been active in the SUSY Photon working group since 2005. We have performed searches for SUSY in the context of general gauge-mediated (GGM) breaking with the lightest neutralino as the next-to-lightest SUSY particle (NLSP) and the gravitino as the lightest (LSP). The neutralino is assumed to decay promptly to a photon and a gravitino. The GGM model allows the strongly interacting SUSY particles to have large production cross sections at the LHC, permitting the exploration of parameter space inaccessible at previous colliders. The first search was performed using events with two isolated high-transverse-energy photons, one or more hadronic jets, and E_T^{miss} in the 36 pb^{-1} data sample collected at 7 TeV in 2010. Stringer and Hanson were members of the analysis team, and Hanson was the editor and contact person for the publication [14]. This was one of the first CMS SUSY publications. Stringer interpreted the results of the search in terms of a Universal Extra Dimensions (UED) model. Such models postulate the existence of extra spatial dimensions in which all Standard Model particles can propagate, leading to a series of excitations, known as Kaluza-Klein towers, for each particle. In a model with one extra dimension, these excitations are characterized by the size of the extra dimension, expressed as the compactification radius, *R*. The GGM SUSY search and the UED interpretation were the subjects of his PhD thesis, completed in June 2011. However, the UED interpretation was not included in the publication of the 2010 data.

The GGM diphoton search was continued with the 2011 data. The publication [15] of the complete 2011 data set at 7 TeV was completed in 2012, now including Stringer's UED interpretation (Stringer moved to the University of Kansas as a postdoc in July 2011).

A new development is a search for electroweak production of a pair of higgsinos (NLSP), each of which decays to a Higgs boson and an LSP. The search channel is then two Higgs bosons, one of which decays to $\gamma\gamma$ and the other to $b\bar{b}$ with E_T^{miss} due to the LSPs. Burt and Hanson are working on this search with colleagues.

2.2.2. Search for New Physics with Long-lived Particles Decaying to Photons and Missing Energy. New heavy particles with long lifetimes are predicted in many models of physics beyond the standard model, such as Hidden Valley or SUSY with gauge-mediated breaking. Such particles may be neutral and decay into photons and invisible particles. Their lifetime is essentially a free parameter of the model. Liu and Hanson implemented a novel method using photons that undergo conversion into e^+e^- pairs. The impact parameter of the photon relative to the beam-beam collision point can be reconstructed using the converted photons. The method is sensitive to lifetimes of the order of 0.1 to 1 ns. A search for a signature of a photon with significant transverse impact parameter in association with $E_{\mathrm{T}}^{\mathrm{miss}}$ was carried out using the 7 TeV data taken in 2011. No signal was observed above the expected background, and the model-independent 95% confidence level upper limits on the cross section varied between 0.11 and 0.21 pb depending on the neutral particle lifetime. The analysis was published [16] and formed the basis for Liu's PhD thesis.

2.2.3. Search for Charged Higgs Boson in *CP*-Violating MSSM and Measurement of the $t\bar{t}$ Cross Section. The study of $t\bar{t}b\bar{b}$ production serves as a potential discovery channel for the charged Higgs in various *CP*-violating Minimal Supersymmetric Standard Models (MSSM). Jeng originally focused on the measurement of the cross section for $t\bar{t}b\bar{b}$, concentrating on *b*-tagging. However, Jeng began working in our group in 2004 as a second-year graduate student, and due to the accident that shut down the LHC from September 2008 until November 2009, he collaborated with other CMS physicists on a measurement of the $t\bar{t}$ cross section [17].

2.3. Angular Analysis and Branching Fraction Measurement of the Decay $B^0 \to K^{*0}\mu^+\mu^-$

Dinardo used the 2011 data set to carry out a full angular analysis of the fully charged decay involving flavor-changing neutral currents (FCNC): $B^0 \to K^{*0}\mu^+\mu^-$. This decay provides opportunities to search for physics beyond the SM. The manuscript has been accepted for publication [18]. The analysis was started before he joined U.C. Riverside, but most of the work was completed while he was a member of our group. The physics analysis he did while at U.C. Riverside made up for the lack of opportunity in his previous postdoc position, and he was offered a faculty position at Milano Bicocca, beginning February 1, 2013.

3. Silicon Tracker

Hanson is a long-time tracker/tracking expert. Before CMS she most recently designed, prototyped, built, and commissioned the Mark II/SLC central drift chamber; carried out simulations to show that tracking was possible at the SSC, designed a central tracking system for the SDC detector for the SSC, and was outer tracking subsystem manager; and built two silicon microvertex detectors for the OPAL experiment at LEP and was in charge of their installation and operation.

We developed a Module Testing and Repair Facility at U.C. Riverside for CMS in a 100 m^2 clean room that had been previously used by DØ physicists for silicon detector work, with a probe station and identical test setups to those at Fermilab and U.C. Santa Barbara. The facility was used to diagnose faulty modules that did not pass the initial tests at Fermilab or U.C. Santa Barbara. Jeng, Liu, Stringer, and Satpathy carried out Strip Tracker Outer Barrel module testing and repair using the facility at U.C. Riverside. The group gained invaluable experience that was later used for tracker integration and commissioning at CERN [19-24]. Pásztor was responsible for the assembly of the front-end hybrid-pitch adapter system at CERN within the Tracker

Hybrid Group. In addition to the tracker integration and commissioning at CERN (Jeng, Satpathy, and Stringer), Stringer played important roles in the Tracker Detector Control System (DCS), including integrating the Strip and Pixel DCS systems (CMS Achievement Award for 2008) and serving as Tracker DCS Chair 2009-2011. Liu worked on the Tracker Web-Based Monitoring (WBM). Undergraduate student Bose worked on the calibration of temperature sensors on the Silicon Strip Tracker modules during the summer of 2008 and completed a search for solar flares using cosmic ray data taken during a commissioning run.

Liu played a major role in the tracking software during its early stages. In particular, he and Hanson developed the reconstruction of photon conversions for the first time in CMS. The conversions were then incorporated into the CMS software for the use of all physicists. The photon conversions were used in the $H \to \gamma\gamma$ analysis, as described in Section 2.1, and then in a search for long-lived particles that decay to photons and missing energy, discussed in Section 2.2.2. The reconstruction of photon conversions was an important software contribution to CMS, and photon conversions have since been used in other physics analyses not related to the U.C. Riverside group.

After Dinardo joined the group in December 2011, the group started to work on the inner pixel tracker and the Phase-1 pixel upgrade [25, 26], shown in Fig. 3. Xu began work on the Tracker DCS, and Dinardo served on Tracker and Pixel Detector Expert On-Call (DOC) shifts. Hanson served on Central Shift Leader shifts.

Long Shutdown 1 (LS1), needed to prepare the LHC for 13-14 TeV running, began in March 2013 and will last until November 2014. During this period both the barrel (BPIX) and forward (FPIX) pixel systems were removed from the experiment for repairs. Burt, who had already begun work on the pixel tracker during the summer of 2012, and Olmedo began in-depth involvement when they relocated to CERN in April 2013. Malberti joined this effort when she joined U.C. Riverside in May 2013. Now all three form a pixel expert team and are taking on major responsibilities. Their work on the repair of the FPIX was highlighted in an article in *Fermilab Today* (see http://www.fnal.gov/pub/today/archive/archive_2013/today13-08-23.html). Burt, Malberti, and Olmedo are also involved with the installation and future commissioning and operation of the pilot blade detector, a prototype pixel detector with eight modules that will be used to test the readout chain for the Phase-1 upgrade of the pixel detector. Given the experience gained during LS1 in the commissioning of the pixel system and in particular with the pilot blade detector, the group will be able to play a leading role in the final integration, operation, and commissioning of the Phase-1 upgrade of the pixel detector.

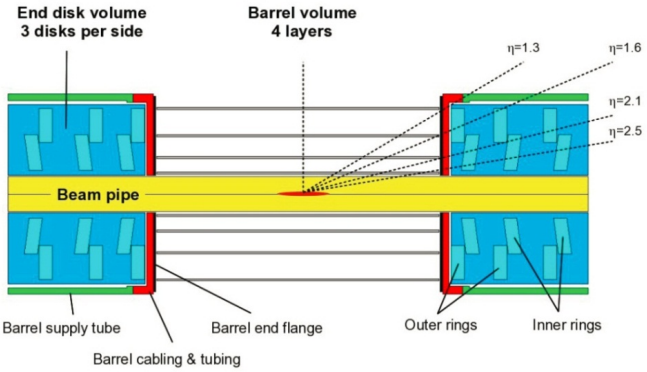

Figure 3: Schematic view of the Phase-1 beam pipe and pixel detector layout, showing the four barrel layers and three end disks on each side

Appendix A: Bibliography and References Cited

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Appendix B: Other Contributions to the CMS Experiment

- G. Hanson, Chair of Analysis Review Committee for "Search for a Pair of Bottom Squarks," SUS-13-018, in progress.

- G. Hanson, Chair of Analysis Review Committee for "Search for Direct Top Squark Pair Production with Higgs Bosons in the Final State in *pp* Collisions at $\sqrt{s}$ = 8 TeV," SUS-13-021, in progress.

- G. Hanson, Chair of Analysis Review Committee for "Evidence for the Standard Model Higgs Boson Decaying to Tau Pairs in Proton-Proton Collisions at $\sqrt{s}$ = 7 and 8 TeV," HIG-13-004, public Physics Analysis Summary prepared for Moriond 2013 and publication in preparation.

- G. Hanson, Chair of Analysis Review Committee for "Search for SUSY Partners of Top and Higgs Using Diphoton Higgs Decays," SUS-13-014, public Physics Analysis Summary prepared for SUSY 2013 and to be submitted to *Phys. Rev. Lett*.

- G. Hanson, Chair of Analysis Review Committee for "Search for the Standard Model Higgs Boson Decaying to Tau Pairs in Association with a *W* or *Z* Boson with the CMS Experiment in *pp* Collisions at $\sqrt{s}$ = 7 and 8 TeV," CMS-PAS-HIG-12-053, public Physics Analysis Summary prepared for Moriond 2013 and being combined with HIG-13-004 for publication.

- G. Hanson, Chair of Analysis Review Committee for "Search for the Standard Model Higgs Boson Decaying to Tau Pairs in Association with a *W* or *Z* Boson," CMS-PAS-HIG-12-051, public Physics Analysis Summary prepared for HCP 2012.

- G. Hanson, Chair of Analysis Review Committee for "Search for Direct Top Squark Pair Production in Events with a Single Isolated Lepton, Jets, and Missing Transverse Energy at $\sqrt{s}$ = 8 TeV," CMS-PAS-SUS-12-023, public Physics Analysis Summary prepared for HCP 2012.

- G. Hanson, Chair of Analysis Review Committee for "Extension: A Search for the Standard Model Higgs Boson Decaying to Tau Pairs (Fully Hadronic and VH) with 5.3 fb^{-1} at 8 TeV," CMS-PAS-HIG-12-032, public Physics Analysis Summary prepared for ICHEP 2012.

- G. Hanson, Chair of Analysis Review Committee for "Search for a *W*' or Techni-ρ Decaying into *WZ* in *pp* Collisions at $\sqrt{s}$ = 7 TeV," EXO-11-041, *Phys. Rev. Lett*. **109**, 141801 (2012).

- R. Stringer, CMS Tracker DCS Chair, January 2009 – July 2011.

Appendix C: PhD Theses

- Hongliang Liu, "Search for New Physics with Long-lived Particles Decaying to Photons and Missing Energy in *pp* Collisions at a Center-of-Mass Energy of 7 TeV with the CMS Experiment at the LHC," defense November 30, 2011. Now employed by Apple Inc.

- Robert Wayne Stringer, "Search for New Physics in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV at the LHC using Di-Photon Events with Large Missing Transverse Energy," defense June 7, 2011. Now a postdoc on CMS at the University of Kansas.

- Geng-Yuan Jeng, "Measurement of the Top Quark Pair Production Cross Section in *pp* Collisions at a Center-of-Mass Energy of 7 TeV with the CMS Experiment at the LHC," defense June 6, 2011. Now a postdoc on ATLAS at the University of Sydney.

Publications with Significant Input from Our Group

1. S. Chatrchyan *et al*., CMS Collaboration, "Angular analysis and branching fraction measurement of the decay $B^0 \to K^* \mu^+ \mu^-$," arXiv:1308.3409 [hep-ex], to be published in *Phys. Lett. B*.

2. S. Chatrchyan *et al*., CMS Collaboration, "Observation of a new boson with mass near 125 GeV in *pp* collisions at $\sqrt{s}$ = 7 and 8 TeV," arXiv:1303.4571 [hep-ex], *J. High Energy Phys.* **06**, 81 (2013).

3. S. Chatrchyan *et al*., CMS Collaboration, "Search for new physics in events with photons, jets, and missing transverse energy in *pp* collisions at $\sqrt{s}$ = 7 TeV," arXiv:1211.4784v2 [hep-ex], *J. High Energy Phys.* **03**, 111 (2013).

4. S. Chatrchyan *et al*., CMS Collaboration, "Search for new physics with long-lived particles decaying to photons and missing energy in *pp* collisions at $\sqrt{s}$ = 7 TeV," arXiv:1207.0627 [hep-ex], *J. High Energy Phys.* **11**, 172 (2012).

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