FINAL REPORT
Study of radiation damage to the CMS Hadronic Endcap Calorimeter and investigation into new physics using multi-boson measurements

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Abstract

This document is the final report for the U.S. D.O.E. Grant No. DE-SC0014088, which covers the period from May 15, 2015 to March 31, 2016.

The funded research covered the study of multi-boson final states, culminated in the measurement of the $W^{\pm}\gamma\gamma$ and, for the first time at an hadronic collider, of the $Z\gamma\gamma$ production cross sections. These processes, among the rarest multi-boson final states measurable by LHC experiments, allow us to investigate the possibility of new physics in a model-independent way, by looking for anomalies in the standard model couplings among electroweak bosons. In particular, these 3-boson final states access quartic gauge couplings; the $W^{\pm}\gamma\gamma$ analysis performed as a part of this proposal sets limits on anomalies in the $WW\gamma\gamma$ quartic gauge coupling.

The award also covered R&D activities to define a radiation-tolerant material to be used in the incoming upgrade of the CMS hadronic endcap calorimeter. In particular, the usage of a liquid-scintillator–based detector was investigated. The research work performed in this direction has been collected in a paper recently submitted for publication in the Journal of Instrumentation (JINST).

1 Overview

Alberto Belloni (Assistant Professor) joined the University of Maryland group in January 2013. He has been working, initially supported by start-up funds, on the CMS detector. He is a US Level-3 manager with responsibility for the Phase-2 upgrade of the CMS central hadron calorimeter (HCAL) and a US Level-4 manager with responsibility for the Phase-1 upgrade of the CMS HCAL front-end electronics. He is also the HCAL upgrade test-beam coordinator, and covered the position of HCAL Phase-2 upgrade EPR manager (review and approval of work pledges in the HCAL collaboration) and edited the endcap calorimeter section of the HCAL Phase-2 technical proposal. Along with postdoc Dr. Joshua Kunkle and (now graduated) student Dr. Christopher Anelli he works on the reconstruction of rare multi-boson final states ($W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$); he also covered the role of Monte-Carlo coordinator for the Standard Model Physics (SMP) group.

The post-doctoral physicist Dr. Joshua Kunkle and (now graduated) student Dr. Christopher Anelli have been supported on the grant during the past year. Dr. Joshua Kunkle is stationed at CERN. He is the HCAL Operation manager, a CMS Level-3 position, and he is the co-convener of the SMP di-boson working group, which comprises about 50-100 physicists. Dr. Anelli graduated in April 2016 with a thesis entitled "Measurement of the $W^{\pm}\gamma\gamma$ Cross Section and Limits on Anomalous Quartic Gauge Couplings in Proton-Proton Collisions at 8 TeV with the CMS Detector", in which he focused on the $W^{\pm}\gamma\gamma$ production cross section and anomalous quartic gauge couplings.

2 Multi-boson Physics with the CMS detector

The data samples collected by the LHC allow for the performance of precision measurements that challenge the theoretical predictions based on the standard model. In particular, the focus of our analysis effort was the search for rare multi-boson final states. While we initially dedicated our attention to the $W^{\pm}\gamma\gamma$ state, we realized that all our analysis methods could be equally applied to the $Z\gamma\gamma$ final state, and provided a substantial, and crucial contribution to the analysis team that was focusing on that final state.

These 3-boson final states have a production cross section that puts them among the rarest electroweak processes that can be reconstructed by LHC experiments. An important feature of these processes is that they are a natural venue to look for anomalies in the electroweak quartic gauge couplings. The framework that we utilized is an effective-field theory expansion in dimension-8 operators. These are the lowest-order operators that could introduce a quartic gauge coupling anomaly without affecting triple gauge couplings, which, so far, we have no evidence of.

The main results of the analysis are summarized by Figs. 1, 2, and 3. They show, respectively, the distribution of $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ candidates; the effect of an anomaly in the quartic gauge coupling L_{T0} on the kinematic of the leading photon in the $W^{\pm}\gamma\gamma$ final state; a cross-check of a background estimate in a control region depleted of signal events. This last plot is interesting because background estimates represented the most complicate part of the analysis. The $W^{\pm}\gamma\gamma$ final state is rare enough that misreconstructing a jet, copiously produced in a proton-proton environment, as a photon can introduce a background of a similar magnitude as the signal. Since it is very difficult to model the probability of incurring in such a misreconstruction in a Monte-Carlo simulation, we devised a data-driven method to estimate this background. This method uses data candidates in regions dominated by backgrounds, and considers separately the cases when jets mimic the leading, the sub-leading, or both photons. The agreement between the background estimate and the data points shows the validity of our method.

Our analysis passed the CMS internal review process, and was approved for public distribution in February 2015. The CMS note that documents the analysis is publicly available [1]. Dr. Christopher Anelli, at the time a graduate student, presented our results at the Lake Louise

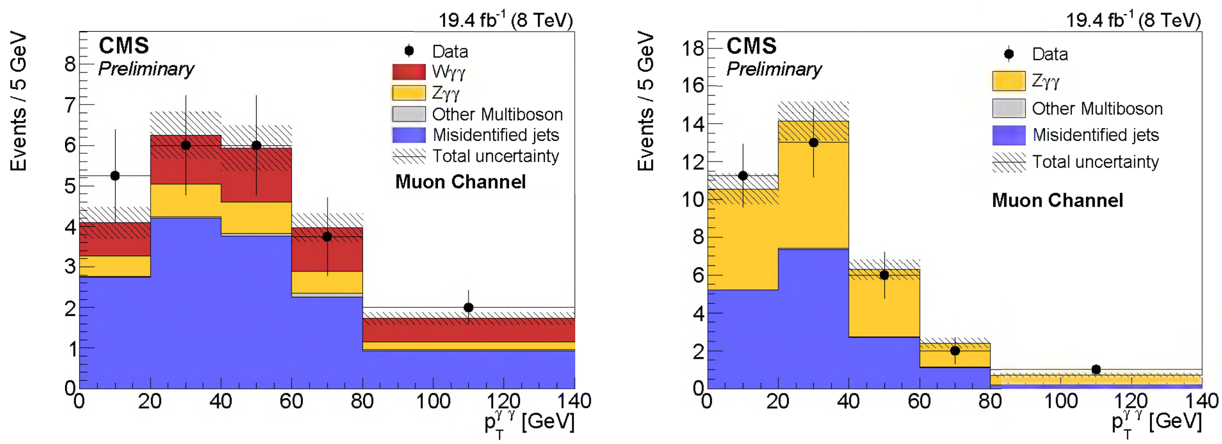

Figure 1: The p_{T} of the diphoton system in the muon channel for the $W^{\pm}\gamma\gamma$ analysis (left) and $Z\gamma\gamma$ analysis (right). The jet misidentification background contribution is determined from data-driven methods. In each plot, the other multiboson contributions are estimated using simulation and are normalized to their production cross section. The hatched band represents the total uncertainty of all background sources, combined in quadrature. The last bin includes all events having $p_T^{\gamma\gamma} > 80$ GeV, but the normalization is to the displayed bin width.

Winter Institute conference, February 7-13, 2016 [2].

3 Radiation-tolerant materials for the CMS Hadron Calorimeter upgrades

The end of Run 1, in 2012, left a significant challenge to the CMS Collaboration. It was observed that the section of the hadronic calorimeter installed at $1.3 < |\eta| < 3.0$ (the Hadronic Endcap, HE) is aging much faster than predicted, and the aging rate is such that very little light would be left well before the originally estimate date for the HE replacement.

We led the proposal to use a liquid-scintillator detector in the areas of the HE that receive the highest radiation dose. Our studies completed the following tasks:

- mechanical design for a liquid-scintillator tile, made with aluminum
- simulation studies of light-collection efficiency as a function of the tile construction parameters
- construction of six container prototypes, with varying characteristics (thickness, reflectivity of aluminum surface, diameter of wavelength-shifting readout optical fiber)
- irradiation of liquid scintillator in the University of Maryland ^{60}Co irradiation facility, and measurement of its radiation tolerance
- measurement of light-collection efficiency using a cosmic-ray telescope at the University of Maryland
- measurement of light-collection efficiency as a function of hit position using a muon beam at the CERN H2 test-beam area

The complete suite of R&D results is reported in a paper that was recently submitted to JINST [3].

The CMS Collaboration ultimately decided to adopt a different technology for the upgrade of the HE, replacing its electromagnetic and hadronic sections with a silicon-based detector, to be followed by a plastic-scintillator hadronic section. In view of this decision, we shifted our focus

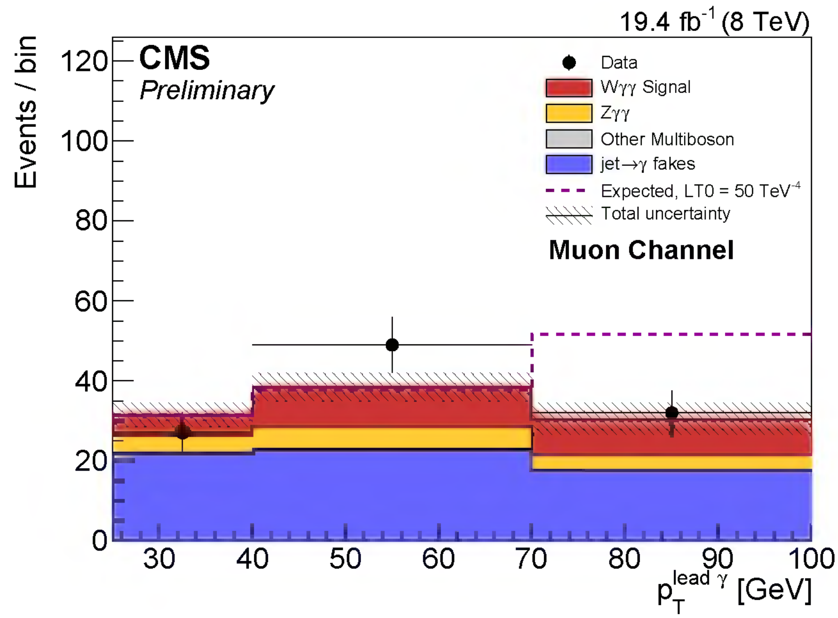

Figure 2: Observed data with predicted background contributions, expected SM $W^{\pm}\gamma\gamma$ signal and the contribution from an aQGC where the $f_{T,0}$ parameter is 50 TeV^{-4} (dashed line).

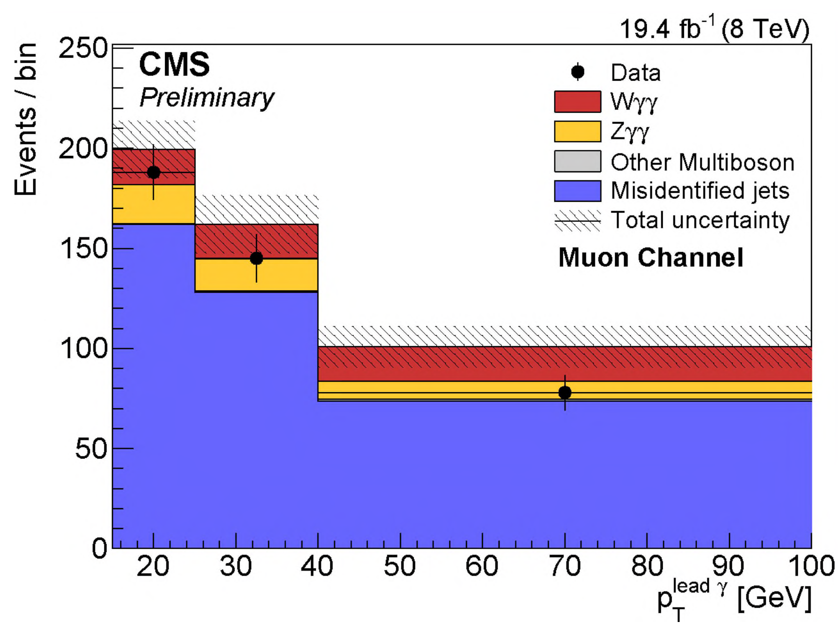

Figure 3: Validation of the data-driven estimates of misidentified electrons and jets signal-like events that have 15 GeV $< p_T^{\mathrm{sublead}} <$ 25 GeV in the muon channel. The misidentified jet and misidentified electron contributions are estimated using data-driven techniques. The $W^{\pm}\gamma\gamma$, $Z\gamma\gamma$ and other multiboson contributions are given by simulation. The hatched area represents the combined uncertainty from all background estimates.

to studying radiation-tolerant plastic materials. Our group led the investigation of a new line of materials: over-doped plastic scintillators. The concentration of light-producing and wavelength-shifting dopants contained in a commercial plastic scintillator is typically optimized to provide maximum light output when the material is not irradiated. With materials specifically produced per our instructions by Eljen Technologies, Sweetwater, TX, we demonstrated that increasing the concentration of dopants, while it reduces the light output of the non-irradiated scintillator, strengthen its radiation tolerance. Indeed, over-doped scintillators became the baseline materials for the Phase-2 upgrade of both the barrel ($|\eta| < 1.3$) and the endcap CMS hadronic calorimeters. The results of our studies of plastic scintillators are collected in a CMS draft note and were approved for public presentation. They were presented by post-doctoral fellow Dr. Geng-Yuan Jeng, with whom the PI collaborates at the University of Maryland, at CALOR16 [4].

References

[1] [CMS Collaboration], "Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ cross sections and limits on dimension-8 effective anomalous gauge couplings at $\sqrt{s}$= 8 TeV," CMS-PAS-SMP-15-008, February 2016, `http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP-15-008/index.html`.

[2] C.R. Anelli, "Measurement of Multi-Boson Final States $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ at CMS," Lake Louise Winter Institute, 7-13 February 2016, `https://indico.cern.ch/event/472587/contributions/1151292/attachments/1225543/1793870/Wgg_Zgg_LakeLouise_Muon.pdf`

[3] A. Belloni, *et al*, "Liquid scintillator tiles for calorimetry," submitted for publication on JINST.

[4] Geng-Yuan Jeng, "Radiation effects on hadronic calorimeters at the LHC," CALOR 16, Daegu, 15-20 May 2016, `https://indico.cern.ch/event/472938/contributions/1150731/attachments/1275340/1891866/CALOR16-Jeng-20160519_final.pdf`

A Presentations

1. 04/20/16 A. Belloni, University of Virginia, invited seminar
   "Constraining the Standard Model with Rare Electroweak Processes: $W\gamma\gamma$ and $Z\gamma\gamma$ in CMS 8 TeV Data"
2. 10/08/15 A. Belloni, Brookhaven Forum 2015: Great Expectations, a New Chapter
   "Standard Model at 13 TeV with the CMS detector"
3. 05/29/15 A. Belloni, Cornell 2015 US CMS Meeting
   "HGC Scintillators R&D"
4. 08/03/16 J. Kunkle, ICHEP2016, University of Chicago
   "Associated production of photons and other gauge bosons at CMS"
5. 08/04/15 J. Kunkle, DPF2015, University of Michigan
   "Multiboson measurements and limits on anomalous gauge couplings with the CMS"
6. 02/07/16 C.R. Anelli, Lake Louise Winter Institute
   "Measurement of Multi-Boson Final States $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ at CMS"

B Notes

1. JINST_040P_0716, "Liquid scintillator tiles for calorimetry ", A. Belloni (and others)
2. CMS DN-2016/010, "Radiation Tolerance Studies of Selected Plastic Scintillators", A. Belloni (and others)

3. CMS-PAS-SMP-15-008, "Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ cross sections and limits on dimension-8 effective anomalous gauge couplings at $\sqrt{s}$= 8 TeV", C. Anelli, A. Belloni, and J. Kunkle
4. CMS AN-2015/162, "Measurement of the $pp \rightarrow W^{\pm}\gamma\gamma$ Final State and Limits on Dimension-8 Effective Anomalous Couplings $\sqrt{s} = 8$ TeV", C. Anelli, A. Belloni, J. Kunkle (and others)
5. CMS CR-2015/269, "Multiboson measurements and limits on anomalous gauge couplings with the CMS experiment, Conference Report", J. Kunkle

C Curriculum Vitae

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Employment

2013-present	Assistant Professor, University of Maryland
2010-2013	Research Associate, Harvard University
2007-2010	Post-doctoral Researcher, Harvard University

Education

September 2007	Massachusetts Institute of Technology, Ph.D in Physics
April-August 2002	Tsukuba University, Research Student
November 2002	Scuola Normale Superiore, Diploma di Licenza, 70/70 cum laude
January 2002	Università degli Studi di Pisa, Diploma di Laurea, 110/110 cum laude
June-August 2000	Fermilab, Summer Student

Honors and Awards

2002-2003	Massachusetts Institute of Technology Presidential Fellow
1997-2001	Member of Classe di Scienze, Scuola Normale Superiore