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1 Executive Summary

The Compact Muon Solenoid (CMS) Experiment is a general purpose particle detector experiment at the Large Hadron Collider (LHC) at the European Laboratory for Nuclear Research (CERN) [1]. The LHC is the world's highest energy particle collider, providing proton-proton collisions up to a center-of-mass energy of 13 TeV. The primary aim of the LHC and the CMS Experiment is to discover new physics at this high energy frontier. In 2012, the discovery of the Higgs boson at the LHC marked a crucial milestone in the Standard Model (SM) of particle physics and ushered in the beginning of a new era of exploration at the high energy frontier [2]. Since this discovery, two key areas of study were the characterization of the new particle to confirm that it is, indeed, the predicted SM Higgs boson and also the examination of possible deviations from the SM that may hint at new physics.

As a member of the CMS collaboration, the main interest of PI Orimoto has been the study of electromagnetic objects (electrons and photons) as a critical ingredient in the characterization of the Higgs boson, and as a window into physics beyond-the-SM (BSM). To this end, the Orimoto group has led numerous physics analyses ranging from SM Higgs boson studies, searches for exotic production and decay of the Higgs boson, as well as searches for supersymmetric particles. Moreover, the Orimoto group has made significant contributions to the CMS electromagnetic calorimeter (ECAL), the sub-detector responsible for the precise measurement of the energies of electrons and photons. The Orimoto group's contributions have been recognized with many leadership roles and high profile conference presentations. This report outlines the group's products and accomplishments from the award period (June 2013 through July 2018).

2 Composition of Research Group

The Orimoto group is led by PI Toyoko Orimoto, who has been a member of the CMS Collaboration since 2006, and an assistant professor of physics at Northeastern University since Oct 2012. Postdoctoral Researcher Andrea Massironi was a member of the group from Jan 2013 through Dec 2018, at which point he began a permanent position at INFN

Milano Biccoca. PhD student Rafael Teixeira de Lima was a member of the group from Sep 2012 through May 2017. Teixeira de Lima graduated in May 2017 and subsequently began a postdoctoral research position with the SLAC ATLAS group. PhD students Tanvi Wamorkar and Abraham Tishelman-Charny joined the group in May 2016 and May 2017, respectively. In addition, PI Orimoto engages with undergraduate coop students who work full time for six month periods at CERN, funded through an NSF sub-award (award number 1624356).

3 Physics Analysis

The Orimoto group has produced a number of significant results with electromagnetic final states, including SM Higgs studies and searches for exotic phenomena.

3.0.1 Higgs Physics: $H \to WW$

$H \to WW$ (HWW) is one of the most statistically powerful Higgs channels at the LHC and also provides an important window into understanding the Higgs couplings and width. Dr. Massironi was a significant contributor to the CMS $H \to WW$ (HWW) analysis group for many years, with a focus on the $WW \to l\nu l\nu$ final state, and served as the group's co-convener from Jan 2015 to Sep 2016. As convener, Dr. Massironi led a team of more than two dozen physicists and was a member of the CMS Higgs Physics Analysis Group Coordination team. One of the major results that the CMS HWW group contributed to under Dr. Massironi's leadership was the combination of Higgs coupling results with Run 1 data from CMS and ATLAS [3]. Fig. 1 shows the best fit values of the $gg \to H \to WW$ cross section and of ratios of cross sections and branching fractions from these combined results. Other important results produced under his convenership include the re-discovery of HWW at $\sqrt{s} = 13\,\text{TeV}$ [4] and the indirect measurement of the Higgs boson width [5]. Dr. Massironi has also contributed to the first exclusive searches of HWW in the associated production and vector boson fusion channels [6], the differential distribution of the Higgs transverse momentum [7], and the measurement of the SM WW cross section [8].

3.0.2 Higgs Physics: Di-Higgs in $bb\gamma\gamma$

Teixeira de Lima and Pi Orimoto were among the the main contributors to the CMS search for di-Higgs production (HH) and exotic phenomena in the final state with two b-quarks and two photons $HH \to bb\gamma\gamma$ (HHbbgg). Di-Higgs production has yet to be observed at the LHC and provides an interesting test of the Higgs self-coupling, as well as potential constraints on new physics. The $bb\gamma\gamma$ final state is among the most promising channels for the di-Higgs search, due to the high branching ratio of $H \to bb$, paired with the clean signature of the two photons from the $H \to \gamma\gamma$ decay. Even more promising is the opportunity to use this channel to probe new phenomena via resonant or nonresonant BSM enhancements. Teixeira de Lima was the lead analyzer on the CMS Run 2 HHbbgg result. In addition to leveraging Teixeira de Lima's expertise in photon identification from his previous work on CMS, this analysis utilized his experience in b-tagging from his Master's thesis on the D-Zero Experiment. Moreover, this work complemented the di-Higgs studies that Dr. Massironi produced (with

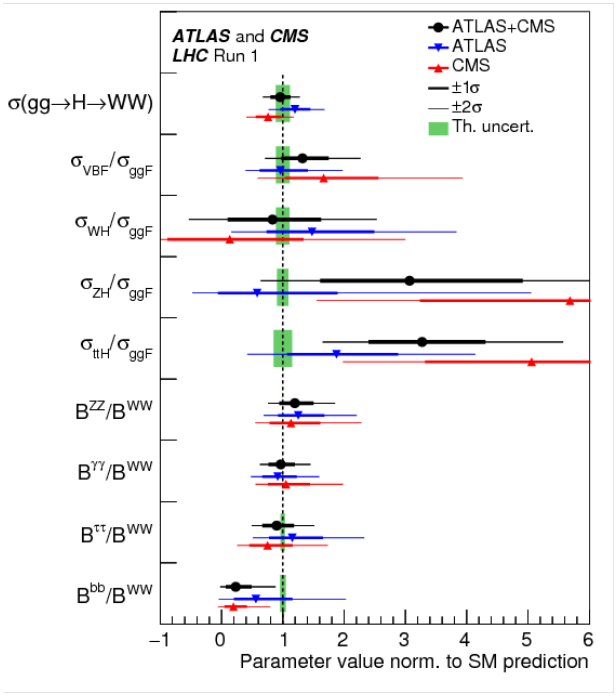

Figure 1: Best fit values of the $gg \rightarrow H \rightarrow WW$ cross section and of ratios of cross sections and branching fractions for the combination of the ATLAS and CMS measurements. Also shown are the results from each experiment. Reproduced from [3].

four b-quarks) for the Les Houches workshop in 2013, and also PI Orimoto's previous work in searches for warped extra dimensions in the two photon final state. The Run 2 HHbbgg result was published in 2018 [9], resulted in the most restrictive constraints on SM di-Higgs production to date, as depicted in Fig. 2. This study, along with the monophoton analysis described in Sec. 3.0.4, constituted the bulk of Teixeira de Lima's dissertation.

3.0.3 BSM Physics: Exotic Higgs Decays in the 4 Photon Final State

As the parameter space for "natural" SUSY has been heavily constrained by the LHC, CMS has expanded its efforts into the wider SUSY landscape. Some supersymmetric extensions of the SM, such as the Next-to-Minimal-Supersymmetric-Standard-Model, predict a light pseudo-scalar particle (a), which the SM Higgs boson could decay to [10]. In addition, if this new particle is below the threshold to produce three π^0 mesons, then the two photon decay channel of the a particle is enhanced. As a result, the four photon final state ($H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$) is a promising channel to discover this new particle. PI Orimoto is the senior member of the analysis, supervising all efforts, and Tanvi Wamorkar is the leading graduate student, producing the entire end-to-end analysis chain. The group plans to produce the first CMS result in this channel by 2019 and a publication with the full LHC Run 2 dataset by early 2020 (which will comprise the bulk of Wamorkar's dissertation).

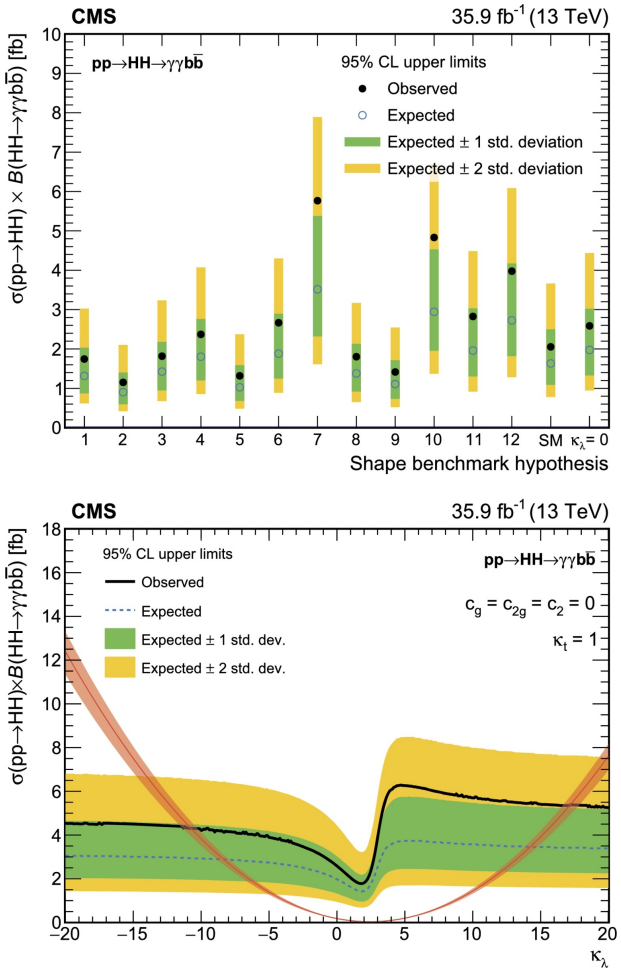

Figure 2: Expected and observed 95% confidence level upper limits on the SM-like HH production cross section times obtained for different nonresonant benchmark models (top); for different values of the effective Higgs boson self-coupling κ_λ (bottom). Reproduced from [9].

3.0.4 BSM Physics: Photon + $p_{\mathrm{T}}^{\mathrm{miss}}$ Final State

Dark matter presents one of the most exciting possibilities for discovery at the LHC. PI Orimoto and Teixeira de Lima made significant contributions to the search for new physics in the low energy monophoton channel. This final state, which consists of a single photon and missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$), can be used to constrain low scale supersymmetry (SUSY)-breaking scenarios and models of dark matter. This analysis probed an unexplored phase space of CMS data, utilizing the parked data program, complementing the traditional high transverse energy searches for SUSY and dark matter. As the senior member of this analysis effort, PI Orimoto oversaw the collaborative contributions from several institutions. Teixeira de Lima's work focused on the development of a novel method to measure the misidentification of electrons as photons. These results were published in Feb 2016 [11]. Fig. 3 shows the expected and observed 95% confidence level upper limits on the cross section times branching ratio, normalized to the SM Higgs cross section, as a function of the neutralino ($\tilde{\chi}_1^0$) mass.

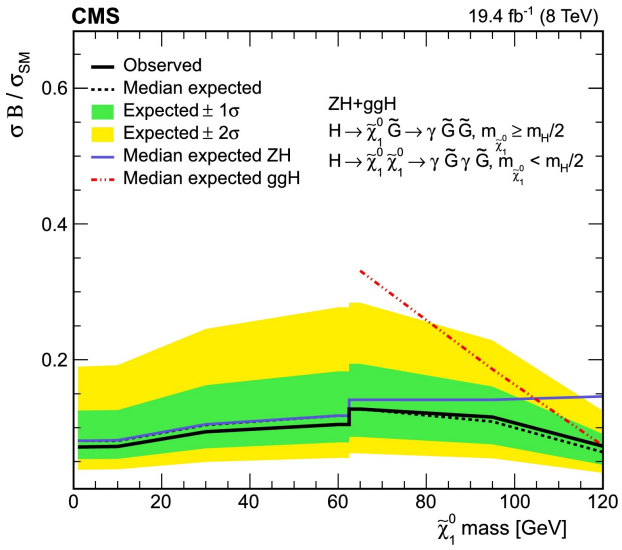

Figure 3: Expected and observed 95% CL upper limits on $\sigma B/\sigma_{\rm SM}$ for $m_H = 125$ GeV as a function of $\tilde{\chi}_1^0$ mass assuming the SM Higgs boson cross sections, for the ZH and ggH channels and their combination. Reproduced from [11].

3.0.5 BSM Physics: Two Photons + $p_{\rm T}^{\rm miss}$ Studies

In conjunction with the group's work on the CMS low energy monophoton result, PI Orimoto and Teixeira de Lima were the driving force in a feasibility study of the two photon+$p_{\rm T}^{\rm miss}$ final state in collaboration with the theorists and experimentalists from the LHC Cross Section Working Group. The two photon+$p_{\rm T}^{\rm miss}$ final state can be used to constrain low scale SUSY-breaking models, as well as scenarios in which the Higgs decays to new particles (one of which decays to two photons, the other which escapes detection). In this study, the sensitivity of the two photon+$p_{\rm T}^{\rm miss}$ final state was explored for 100 fb^{-1} of 14 TeV LHC data using the DELPHES simulation package. These results were published in CERN Yellow Report 4 [12].

3.0.6 BSM Physics: SUSY in the Two Photons + $p_{\rm T}^{\rm miss}$ Final State

PI Orimoto collaborated with CERN researcher Maurizio Pierini and Princeton University graduate student Joshua Hardenbrook on the search for SUSY in the two photon+$p_{\rm T}^{\rm miss}$ +jets final state. Events containing two highly energetic photons and significant $p_{\rm T}^{\rm miss}$ can result from new physics processes in general gauge mediated models of SUSY breaking. This study examined a complementary phase space to the low energy monophoton study and focused on the application of the novel "razor" method, which takes advantage of the kinematics of heavy pair production to discriminate against backgrounds and mis-measurements of $p_{\rm T}^{\rm miss}$. This analysis, published in Oct 2015, was the official and final 8 TeV CMS result on the search for SUSY in this final state [13].

4 Electromagnetic Calorimeter

The CMS electromagnetic calorimeter (ECAL) is a high-resolution, hermetic, and homogeneous calorimeter made of 75,848 scintillating lead tungstate crystals [14]. The excellent performance of the CMS ECAL was crucial to the discovery of the Higgs boson and will play an important role in any new discoveries involving electrons or photons. As such, the Orimoto group has taken a leading role in the operation, maintenance, and upgrade of ECAL.

4.0.1 ECAL: Data Acquisition System

Dr. Massironi, Teixeira de Lima, and Wamorkar were responsible for the maintenance and development of the ECAL data acquisition system (DAQ), serving as ECAL DAQ experts-on-call. Dr. Massironi and Teixeira de Lima played a crucial role during the Run 2 recommissioning period. In particular, Teixeira de Lima took a leading role in the upgrading of the ECAL DAQ to the new CMS Trigger Control and Distribution System. In recognition of his work, Teixeira de Lima was recognized with a CMS Achievement Award in 2015 "for his leading contributions to ECAL DAQ development and his support of ECAL DAQ installations at P5 and B904".

4.0.2 ECAL: Detector Performance Group

Dr. Massironi served as the ECAL Detector Performance Group (DPG) convener from Sep 2016 until Aug 2018. As convener, Massironi oversaw the work of approximately 100 collaborators working in calibration, alignment, monitoring, test beam studies, and energy corrections, to ensure the continuing excellent performance of the ECAL. Prior to his term as ECAL DPG convener, Dr. Massironi led the effort in ECAL alignment with electrons, a key ingredient for achieving high energy resolution and optimal identification of electrons and photons. For his many contributions, Dr. Massironi was awarded a 2018 CMS Achievement Award "for outstanding work on the ECAL performance, for the development of the ECAL alignment procedure and for dedicated support of the data acquisition system." Since 2016, Wamorkar has taken over the responsibility of the ECAL alignment. In addition, Tishelman-Charny has been working with Dr. Massironi and PI Orimoto on studies of the ECAL local reconstruction, studying the effects of time shifts on the measurement of energies.

4.0.3 ECAL Upgrade

The High Luminosity upgrade of the LHC (HL-LHC) will provide unprecedented instantaneous and integrated luminosity in an extremely challenging environment. As such, the CMS detector must be upgraded to continue its excellent performance in the HL-LHC period (2026-2038). Among the main physics benchmarks for the HL-LHC are the discovery of di-Higgs production (as described above in Sec. 3.0.2) and the potential discovery of new BSM physics. During this award period, the Orimoto group steadily ramped up involvement in the CMS Phase II Upgrade for HL-LHC. For the Phase II upgrade of the ECAL, the forward endcap portion of the detector will be replaced, while the central barrel region (EB) will undergo a replacement of the readout electronics [15]. The EB electronics must be replaced

to meet the more stringent requirements of the upgraded CMS trigger system and to mitigate the effects of the large number of overlapping events (pileup) expected at the HL-LHC. From 2015 through 2018, PI Orimoto worked with six undergraduate coop students and PhD student Tishelman-Charny on simulation studies, test beam data analysis, and laboratory bench tests for the EB electronics upgrade.

4.0.4 ECAL Editorial Board

PI Orimoto has served as a member of the ECAL Editorial Board (EEB) since 2013 and as the chair of the EEB since Jan 2014. The EEB has the responsibility of ensuring that all ECAL publications and presentations are of the highest quality. The EEB scrutinizes and rehearses all ECAL abstracts, conference presentations, proceedings, and journal publications.

5 List of Publications

Articles with significant contributions from the Orimoto group during the award period (July 2013 through June 2018) are listed below.

Reviewed articles

[1] A. M. Sirunyan *et al.* [CMS Collaboration], "Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV," currently under review (submitted to Physics Letters B on June 13, 2018).

[2] A. M. Sirunyan *et al.* [CMS Collaboration], "Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV," Phys. Lett. B **788**, 7 (2019).

[3] V. Khachatryan *et al.* [CMS Collaboration], "Measurement of the transverse momentum spectrum of the Higgs boson produced in pp collisions at $\sqrt{s} = 8$ TeV using $H \to WW$ decays," Journal of High Energy Physics **1703**, 032 (2017).

[4] V. Khachatryan *et al.* [CMS Collaboration], "Search for exotic decays of a Higgs boson into undetectable particles and one or more photons," Physics Letters B **753**, 363 (2016).

[5] T. Adams *et al.*, "Beam test evaluation of electromagnetic calorimeter modules made from proton-damaged $PbWO_4$ crystals," Journal of Instrumentation **11**, no. 04, P04012 (2016).

[6] ATLAS and CMS Collaborations, "Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV," Journal of High Energy Physics **1608**, 045 (2016).

[7] V. Khachatryan *et al.* [CMS Collaboration], "Measurement of the W^+W^- cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous gauge couplings," European Physical Journal C **76**, no. 7, 401 (2016).

[8] V. Khachatryan *et al.* [CMS Collaboration], "Search for Higgs boson off-shell production in proton-proton collisions at 7 and 8 TeV and derivation of constraints on its total decay width," Journal of High Energy Physics **1609**, 051 (2016).

[9] V. Khachatryan *et al.* [CMS Collaboration], "Search for supersymmetry with photons in pp collisions at $\sqrt{s}$=8 TeV," Physical Review D **92**, no. 7, 072006 (2015).

[10] V. Khachatryan *et al.* [CMS Collaboration], "Search for a Higgs Boson in the Mass Range from 145 to 1000 GeV Decaying to a Pair of W or Z Bosons," Journal of High Energy Physics **1510**, 144 (2015).

[11] V. Khachatryan *et al.* [CMS Collaboration], "Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at sqrt(s) = 8 TeV," Journal of Instrumentation **10**, no. 08, P08010 (2015).

[12] V. Khachatryan *et al.* [CMS Collaboration], "Performance of Electron Reconstruction and Selection with the CMS Detector in Proton-Proton Collisions at s = 8 TeV," Journal of Instrumentation **10**, no. 06, P06005 (2015).

[13] V. Khachatryan *et al.* [CMS Collaboration], "Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV," European Physical Journal C **75**, no. 5, 212 (2015).

[14] S. Chatrchyan *et al.* [CMS Collaboration], "Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in *pp* Collisions at $\sqrt{s} = 7$ TeV," Journal of Instrumentation **8**, P09009 (2013).

[15] 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," Journal of High Energy Physics **1306**, 081 (2013).

Non-reviewed articles

[1] CMS Collaboration, "The Phase-2 Upgrade of the CMS Barrel Calorimeters Technical Design Report," CERN-LHCC-2017-011. CMS-TDR-015.

[2] D. de Florian *et al.* [LHC Higgs Cross Section Working Group], "Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector," arXiv:1610.07922 [hep-ph].

[3] CMS Collaboration, "Higgs to WW measurements with 15.2 fb^{-1} of 13 TeV proton-proton collisions," CMS-PAS-HIG-16-021.

[4] CMS Collaboration, "Search for high mass Higgs to WW with fully leptonic decays using 2015 data," CMS-PAS-HIG-16-023.

[5] CMS Collaboration, "First results on Higgs to WW at $\sqrt{s} = 13$ TeV," CMS-PAS-HIG-15-003.

[6] CMS Collaboration, "Measurement of the WW cross section pp collisions at sqrt(s)=13 TeV," CMS-PAS-SMP-16-006.

[7] CMS Collaboration [CMS Collaboration], "VH with H→WW→ $\ell\nu\ell\nu$ and V→jj," CMS-PAS-HIG-13-017.

6 List of Conference Presentations

Below is a list a conference presentations from the Orimoto group for the period of this grant (July 2013 - June 2018).

Prof. Toyoko Orimoto

- "Results from CMS," on behalf of the CMS Collaboration, Miami Conference, Fort Lauderdale FL, Dec 2017.
- "High precision electromagnetic calorimetry with 40 MHz readout: the CMS crystal ECAL for the High-Luminosity LHC," on behalf of the CMS Collaboration, IEEE Nuclear Science Symposium and Medical Imaging Conference, Atlanta, GA, Oct 2017.
- "Recent Run 2 Results from the CMS Collaboration," on behalf of the CMS Collaboration, US LHC Users Association (USLUA) Annual Meeting, Berkeley, CA, Nov 2016.
- "Design studies for the Phase II upgrade of the CMS Barrel Electromagnetic Calorimeter", on behalf of the CMS Collaboration, International Conference on High Energy Physics (ICHEP16), Chicago, IL, Aug 2016.
- "Search for New Physics in the Low MET Monophoton Channel with the CMS Detector," on behalf of the CMS Collaboration, American Physical Society Meeting of the Division of Particles and Fields Meeting 2015, Ann Arbor, MI, Aug 2015.
- "Search for New Physics in the Low MET Monophoton Channel with the CMS Detector," on behalf of the CMS Collaboration, Phenomenology Symposium 2015, Pittsburgh, PA, May 2015.
- "Mono- and Di-photon Searches at the LHC," on behalf of the CMS Collaboration, Astroparticle Physics 2014, Amsterdam, NL, June 2014.

Dr. Andrea Massironi

- "Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC," Calorimetry for the High Energy Frontier (CHEF), Lyon, France, Oct 2017.
- "Overview of SM and Higgs results at ATLAS and CMS," 15th Conference on Flavor Physics and CP Violation (FPCP), Prague, Czech Republic, Jun 2017.
- "Is the Model Standard? Experimental results on SM and Higgs physics," XVI Incontri di fisica delle alte energie (IFAE), Trieste, Italy, Apr 2017.
- "Measurements of Higgs boson production and properties in the WW decay channel using the CMS detector," International Conference on High Energy Physics (ICHEP), Chicago, IL, Aug 2016.

- "Electromagnetic calorimetry at the highest energy and intensity proton-proton collider: CMS ECAL performance at LHC Run II and prospects for high luminosity LHC," 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference, San Diego, CA, Oct 2015.
- "Precision electromagnetic calorimetry at the energy frontier: CMS ECAL at LHC Run 2," Meeting of the APS Division of Particles and Fields, Ann Arbor, MI, Aug 2015.
- "SM results: Higgs boson to vector boson decays in ATLAS and CMS," Higgs Coupling, Torino, Italy, Oct 2014.
- "Evolution studies of the CMS ECAL endcap response and upgrade design options for High-Luminosity LHC", Large Hadron Collider Physics (LHCP), New York, NY, Jun 2014 (poster).
- "VBS/VBF [Vector Boson Scattering/Vector Boson Fusion] from CMS," Large Hadron Collider Physics (LHCP), New York, NY, Jun 2014.
- "Higgs to WW to $l\nu l\nu$ results from CMS," Higgs Hunting, Orsay, France, July 2013.

Rafael Teixeira de Lima

- "Search for Higgs Pair Production in the final state with two photons and two b jets at 13 TeV," Higgs Coupling, Stanford, CA, Nov 2016.
- "Search for Higgs Pair Production in the final state with two photons and two b jets at 13 TeV, " USLUA Annual Meeting, Berkeley, CA Nov 2016.
- "Overview of energy reconstruction and electron and photon performances with the CMS ECAL in Run II," CALOR 2016, Daegu, South Korea, May 2016.
- "Search strategies for exotic decays of the Higgs boson into two photons plus missing energy," APS April Meeting 2016, Salt Lake City, UT, Apr 2016.
- "Exotic decays of the Higgs boson with photons and MET: CMS Run I results and projections for LHC Run II," LHCC meeting, Meyrin, Switzerland, Mar 2016 (poster).
- "Young Scientist Forum: Search for the exotic decay of the Higgs boson in the low ET monophoton final state with the CMS Detector," Higgs Hunting, Orsay, France, July 2015.

Tanvi Wamorkar

- "The performance of the CMS ECAL data acquisition system at LHC Run 2," 14th Pisa meeting on advanced detectors (ELBA), La Biodola, Italy, May 2018 (poster).
- "CMS ECAL Calibration & Alignment," 14th Pisa meeting on advanced detectors (ELBA), La Biodola, Italy, May 2018 (poster).

7 Conclusions

During this award period, PI Orimoto developed coherent research program, emphasizing important physics studies in a number of compelling and complementary channels, and integrating the group's physics expertise with challenging and critical detector-related work. The group produced numerous high-impact publications, gained valuable leadership roles, and was also recognized with important presentations at major conferences. Moreover, PI Orimoto successfully saw through the graduation of her first PhD student, Teixeira de Lima, and the advancement of her first postdoctoral researcher to a permanent position.

8 Acknowledgements

PI Orimoto would like to acknowledge the support of the US Department of Energy and the National Science Foundation.

9 References

[1] CMS Collaboration, "The CMS experiment at the CERN LHC," *JINST.* **3**, S08004 (2008).

[2] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV," JHEP **1306**, 081 (2013).

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[4] A. M. Sirunyan *et al.* [CMS Collaboration], "Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV," currently under review (submitted to Physics Letters B on June 13, 2018).

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[8] V. Khachatryan *et al.* [CMS Collaboration], "Measurement of the W^+W^- cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous gauge couplings," European Physical Journal C **76**, no. 7, 401 (2016).

[9] A. M. Sirunyan *et al.* [CMS Collaboration], "Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final state in pp collisions at $\sqrt{s} = 13$ TeV," Phys. Lett. B **788**, 7 (2019).

[10] U. Ellwanger, C. Hugonie and A. M. Teixeira, "The Next-to-Minimal Supersymmetric Standard Model," Phys. Rept. **496**, 1 (2010).

[11] V. Khachatryan *et al.* [CMS Collaboration], "Search for exotic decays of a Higgs boson into undetectable particles and one or more photons," Physics Letters B **753**, 363 (2016).

[12] D. de Florian *et al.* [LHC Higgs Cross Section Working Group], "Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector," doi:10.23731/CYRM-2017-002 arXiv:1610.07922 [hep-ph].

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[14] S. Chatrchyan *et al.* [CMS Collaboration], "Performance and Operation of the CMS Electromagnetic Calorimeter," JINST **5**, T03010 (2010).

[15] CMS Collaboration, "The Phase-2 Upgrade of the CMS Barrel Calorimeters Technical Design Report," CERN-LHCC-2017-011. CMS-TDR-015.