SEARCH FOR RESONANT DOUBLE HIGGS PRODUCTION WITH bbZZ DECAYS IN THE $b\bar{b}\ell\ell\nu\bar{\nu}$ FINAL STATE IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

by

Rami Kamalieddin

A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfilment of Requirements

For the Degree of Doctor of Philosophy

Major: Physics and Astronomy

Under the Supervision of Professor Ilya Kravchenko

Lincoln, Nebraska

May, 2019

SEARCH FOR RESONANT DOUBLE HIGGS PRODUCTION WITH bbZZ DECAYS IN THE $b\bar{b}\ell\ell\nu\bar{\nu}$ FINAL STATE IN pp COLLISIONS AT $\sqrt{s} = 13$ TeV

Rami Kamalieddin, Ph.D.

University of Nebraska, 2019

Advisers: Ilya Kravchenko

Since the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments, most of the quantum mechanical properties that describe the long-awaited Higgs boson have been measured. Due to the outstanding work of the LHC, over a hundred of fb^{-1} of data have been delivered to both experiments. Finally, it became sensible for analyses teams to start working with a very low cross section processes, which made it possible to observe rare decay modes of the Higgs boson, e.g., a recent success in observing ttH and VHbb processes. One of the main remaining untouched topics is a double Higgs boson production. However, additional hundred of fb^{-1} per year from the HL-LHC will not necessarily help us much with the SM double Higgs physics, the process may remain unseen even in the most optimistic scenarios. The solution is to work in parallel on new reconstruction and signal extraction methods as well as new analysis techniques to improve the sensitivity of measurements. This thesis is about both approaches: we have used the largest available dataset at the time the analysis has been performed and developed/used the most novel analysis methods. One of such methods is the new electron identification algorithm that we have developed at the CMS electron identification group, to which I have had a privilege to contribute during several years of my stay at CERN.

The majority of this thesis is devoted to techniques for the first search at the LHC for the double Higgs boson production mediated by a heavy narrow-width resonance

in the $b\bar{b}ZZ$ channel: $X \to HH \to b\bar{b}ZZ^* \to b\bar{b}\ell\ell\nu\bar{\nu}$. The measurement searches for a resonant production of a Higgs boson pair in the range of masses of the resonant parent particle from 250 to 1000 GeV using 35.9 fb^{-1} of data taken in 2016 at 13 TeV. Two spin scenarios of the resonance are considered: spin 0 and spin 2. In the absence of the evidence of the resonant double Higgs boson production from the previous searches, we proceed with setting the upper confidence limits.

"... a place for a smart quote!"

Lenin, 1922.

ACKNOWLEDGMENTS

This will be a longgggg list!

Table of Contents

List of Figures

List of Tables

Chapter *1*

Conclusions

This thesis is about the search for the double Higgs boson production mediated by the intermediate KK graviton and separately by the radion heavy resonances in the $bbZZ$ channel: one of the Higgs bosons decays to two $\mathrm{q_b}$quarks while the other decays to a pair of Zbosons which, in turn, decay to a pair of neutrinos and a pair of electrons or muons. For this measurement we used 2016 data set with the integrated luminosity of $35.9 fb^{-1}$ collected by the CMS experiment at the LHC in the proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$.

No statistically significant deviations from the SM predictions for background processes have been observed, and 95% upper confidence limits are reported for production cross section of a KK graviton/radion times the branching fraction of the subsequent decay into an HH system. The limits are derived for resonance masses in the 250 GeV to 1 TeV range.

This analysis became public in November 2018 [**?**]. Now, according to the CMS Physics Coordination, CMS wants to see a combination of this analysis with the other $bbZZ$ analysis, which is focused on the 2 b jets, 2 leptons, 2 jets signature. Currents plans are to produce a paper for the Physical Review D (PRD), where we will report the best limits for all available $bbZZ$ channels. Of course, prior to the grand $bbZZ$ merge, each analysis combines the data from both dimuon and dielectron channels.

The mass range to be covered in the combined measurement is also from 250 GeV to 1000 GeV.

CERN guide, S'Cool Lab teacher, Finance Club admin, Boxing Club coach

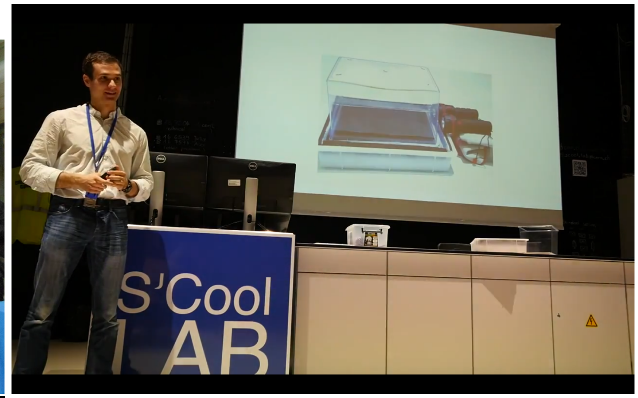
It has been a great pleasure to stay at CERN for four years. From the bottom of my heart I want to thank my adviser and my HEP group for such an opportunity. I have exploited all the possible areas of science, outreach, fun, and joy available at CERN. Well, almost all, and I know it is ridiculous, but I have not tried skiing...

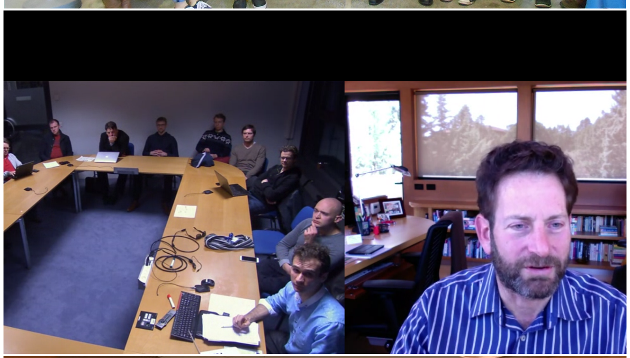
I have been an official CERN guide, giving people tours to Antimatter Decelerator, ATLAS control room, The Low Energy Ion Ring complex, Proton Synchrotron, LHC control room, Data Centre, The SM18 facility (a world leading magnet test facility for testing magnets and instrumentation at low temperature and high currents), The Alpha Magnetic Spectrometer control room. Audience ranged from middle school kids to emeritus professors of science.

Also I have been a teacher at the S'Cool Lab where high school students have a chance to come to CERN and build at this "cool" laboratory a real experimental setup and then conduct the experiment on their own.

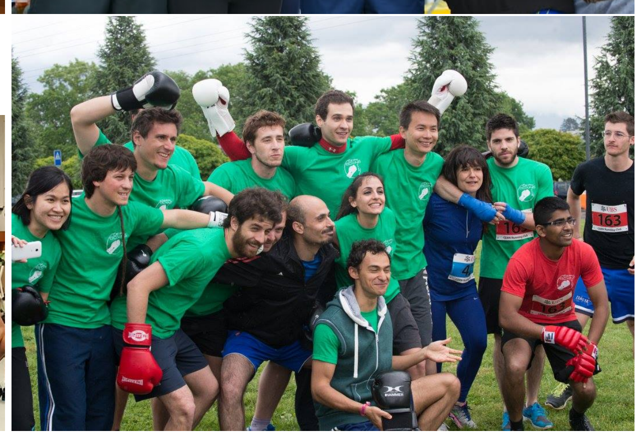
For more than a year I have been an administrative officer at the CERN Finance Club. I have been inviting top professionals from the finance and fintech companies to give talks at our club, I have started the quant group at the club, and have been the first to optimise our portfolio of stocks using Monte Carlo methods and also later with the minimisation technique. needless to say, that I learnt all those tools in High Energy Physics!

Last but not least, my friends from the CERN Powerlifting club introduced me to the Boxing Club. The rest is a history. I have been training people with the goal to improve their health. As a side effect, some picked up self-defence, others had fun and found themselves truly addicted to this combination of the hard work and laughter, and a few even became very much into the world of the intelligent boxing, which is about strategy and outworking the opponent.


S'Cool




The road from Research to Finance
a well trodden path for high-energy physicists?
Luis del Pozo
Management Consultant;
Managing Principal At Capco
Maneesh Wadhwa
Head Innovation Management
Six Swiss Exchange
Pratibha Vikas
Group Head Operational Risk Management
Rami Kamalieddin
PhD Student at University of Nebraska-Lincoln,
CERN Finance Club Admin



References

[1] Richard Phillips Feynman, Robert Benjamin Leighton, and Matthew Sands. *The Feynman lectures on physics; New millennium ed.* Basic Books, New York, NY, 2010. Originally published 1963-1965.

[2] Savas Dimopoulos, Stuart Raby, and Frank Wilczek. Proton decay in supersymmetric models. *Physics Letters B*, 112(2):133 – 136, 1982.

[3] David J Griffiths. *Introduction to elementary particles; 2nd rev. version.* Physics textbook. Wiley, New York, NY, 2008.

[4] Jennifer Ouellette. Einstein's quest for a unified theory. *APS*, 2015.

[5] Erwin Schrödinger. *Statistical thermodynamics; 2nd ed.* Cambridge Univ. Press, Cambridge, 1952.

[6] E A Davis and Isabel Falconer. *J.J. Thompson and the discovery of the electron.* Taylor and Francis, Hoboken, NJ, 2002.

[7] Oreste Piccioni. *The Discovery of the Muon*, pages 143–162. Springer US, Boston, MA, 1996.

[8] Carl Bender. Mathematical physics.

[9] G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Phys. Rev. Lett.*, 9:36–44, Jul 1962.

[10] M. L. Perl, G. S. Abrams, and et al Boyarski. Evidence for anomalous lepton production in $e^+ - e^-$ annihilation. *Phys. Rev. Lett.*, 35:1489–1492, Dec 1975.

[11] K. Kodama et al. Observation of tau neutrino interactions. *Phys. Lett.*, B504:218–224, 2001.

[12] S. M. Bilenky. Neutrino in Standard Model and beyond. *Phys. Part. Nucl.*, 46(4):475–496, 2015.

[13] Eric W. Weisstein. Fundamental forces.

[14] S Chandrasekhar. *Newton's principia for the common reader*. Oxford Univ., Oxford, 2003. The book can be consulted by contacting: PH-AID: Wallet, Lionel.

[15] Hanoch Gutfreund and Jurgen Renn. *The road to relativity: the history and meaning of Einstein's "The foundation of general relativity" : featuring the original manuscript of Einstein's masterpiece*. Princeton University Press, Princeton, NJ, Apr 2015.

[16] J. Butterworth. *Smashing Physics*. Headline Publishing Group, 2014.

[17] W N Cottingham and D A Greenwood. *An Introduction to the Standard Model of Particle Physics; 2nd ed.* Cambridge Univ. Press, Cambridge, 2007.

[18] C. Patrignani et al. Review of Particle Physics. *Chin. Phys.*, C40(10):100001, 2016.

[19] Andrew Wayne. QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga by Silvan S. Schweber. *The British Journal for the Philosophy of Science*, 46(4):624–627, 1995.

[20] Michelangelo L Mangano. Introduction to QCD. (CERN-OPEN-2000-255), 1999.

[21] Matt Strassler. Of particular significance: Conversations about science with theoretical physicist matt strassler.

[22] S.L. Glashow. Partial symmetries of weak interactions. *Nucl.Phys.*, 22:579–588, 1961.

[23] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13:321–323, Aug 1964.

[24] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13:508–509, Oct 1964.

[25] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble. Global conservation laws and massless particles. *Phys. Rev. Lett.*, 13:585–587, Nov 1964.

[26] Pauline Gagnon. *Who cares about particle physics? : making sense of the Higgs boson, the Large Hadron Collider and CERN.* Oxford University Press, 2016.

[27] Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model. Technical Report CMS-PAS-HIG-14-009, CERN, Geneva, 2014.

[28]

[29] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 07:079, 2014.

[30] Thomas Junk. Confidence level computation for combining searches with small statistics. *Nucl.Instrum.Meth.*, A434:435, 1999.

[31] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J.*, C71:1554, 2011. [Erratum: Eur. Phys. J.C73,2501(2013)].

[32] SM Higgs Combination. Technical Report CMS-PAS-HIG-11-011, CERN, Geneva, 2011.

[33] Matthew J. Dolan, Christoph Englert, and Michael Spannowsky. New Physics in LHC Higgs boson pair production. *Phys. Rev.*, D87(5):055002, 2013.

[34] S. Frixione, P. Nason, and C. Oleari. Matching nlo qcd computations with parton shower simulations: the powheg method. *JHEP*, 11:070, 2007.

[35] S. Agostinelli et al. GEANT4—a simulation toolkit. *Nucl. Instrum. Meth. A*, 506:250, 2003.

[36] Gionata Luisoni, Paolo Nason, Carlo Oleari, and Francesco Tramontano. $HW^{\pm}$/HZ + 0 and 1 jet at NLO with the POWHEG BOX interfaced to GoSam and their merging within MiNLO. *JHEP*, 10:083, 2013.

[37] Comparison of nuisances for background only case, 350 GeV mass hypothesis. http://rkamalie.web.cern.ch/rkamalie/feb12/Comparison_of_nuisances_expectedSignal0_350.html

[38] Comparison of nuisances for s+b case, 350 GeV mass hypothesis. http://rkamalie.web.cern.ch/rkamalie/feb12/Comparison_of_nuisances_expectedSignal1_350.html

[39] k-factor for DY/Z. https://twiki.cern.ch/twiki/bin/viewauth/CMS/SummaryTable1G25ns#DY_Z.

[40] The LHC Higgs cross-section working group. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHC

[41] Standard Model Cross Sections for CMS at 13 TeV. https://twiki.cern.ch/twiki/bin/viewauth/CMS/StandardModelCrossSectionsat13TeVInclusive.

[42] SM Higgs production cross sections at sqrt(s) = 13 TeV. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV#ZHllH_H_l_

[43] NNLO+NNLL top-quark-pair cross sections. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Ttb

[44] Single Top Cross sections. https://twiki.cern.ch/twiki/bin/viewauth/CMS/SingleTopSigma.

[45] CMS GEN XSEC Task Force. https://twiki.cern.ch/twiki/bin/viewauth/CMS/GenXsecTaskForce#S

[46] SM Higgs Branching Ratios and Total Decay Widths (update in CERN Report4 2016). https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR#Higgs_2_gauge_b

[47] Ryan Gavin, Ye Li, Frank Petriello, and Seth Quackenbush. W Physics at the LHC with FEWZ 2.1. *Comput. Phys. Commun.*, 184:208, 2013.

[48] Stefano Frixione, Paolo Nason, and Giovanni Ridolfi. A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction. *JHEP*, 09:126, 2007.

[49] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP*, 07:079, 2014.

[50] Gunter Zech. Upper Limits in Experiments with Background Or Measurement Errors. *Nucl. Instrum. Meth.*, A277:608, 1989.

[51] A. L. Read. Presentation of search results: the CLs technique. *J. Phys. G: Nucl. Part. Phys.*, 28, 2002.

[52] Rikkert Frederix, Emanuele Re, and Paolo Torrielli. Single-top t-channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO. *JHEP*, 09:130, 2012.

[53] Johan Alwall et al. Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions. *Eur. Phys. J. C*, 53:473–500, 2008.

[54] Serguei Chatrchyan et al. Determination of jet energy calibration and transverse momentum resolution in CMS. *JINST*, 6:P11002, 2011.

[55] John M. Campbell and R. K. Ellis. MCFM for the Tevatron and the LHC. *Nucl. Phys. Proc. Suppl.*, 205-206:10, 2010.

[56] Emanuele Re. Single-top Wt-channel production matched with parton showers using the POWHEG method. *Eur. Phys. J.*, C71:1547, 2011.

[57] Gael L. Perrin, Pedro Fernandez Manteca. Muon Identification and Isolation Scale-Factors on 2016 Dataset. `https://indico.cern.ch/event/611558/contributions/2465881/attachments/1407735/2151747/TnP_06_02_2017.pdf`.

[58] CMS Muon POG. Tracking SFs on the full 2016 data. `https://twiki.cern.ch/twiki/bin/view/CMS/MuonWorkInProgressAndPagResults#Results_on_the_full_2016_data`.

[59] Gael L. Perrin. Double Muon trigger efficiency per-leg approach. `https://indico.cern.ch/event/636555/contributions/2577291/attachments/1453162/2241537/TnP_DoubleMuSF_03_05_17.pdf`.

[60] Peisi Huang, Aniket Joglekar, Min Li, and Carlos E. M. Wagner. Corrections to Di-Higgs Production with Light Stops and Modified Higgs Couplings. 2017.

[61] Grace Dupuis. Collider Constraints and Prospects of a Scalar Singlet Extension to Higgs Portal Dark Matter. *JHEP*, 07:008, 2016.

[62] Shinya Kanemura, Kunio Kaneta, Naoki Machida, Shinya Odori, and Tetsuo Shindou. Single and double production of the Higgs boson at hadron and lepton colliders in minimal composite Higgs models. *Phys. Rev.*, D94(1):015028, 2016.

[63] Alexandra Oliveira. Gravity particles from Warped Extra Dimensions, predictions for LHC. 2014.

[64] Oleg Antipin, David Atwood, and Amarjit Soni. Search for RS gravitons via W(L)W(L) decays. *Phys. Lett.*, B666:155–161, 2008.

[65] A. Liam Fitzpatrick, Jared Kaplan, Lisa Randall, and Lian-Tao Wang. Searching for the Kaluza-Klein Graviton in Bulk RS Models. *JHEP*, 09:013, 2007.

[66] Kaustubh Agashe, Hooman Davoudiasl, Gilad Perez, and Amarjit Soni. Warped Gravitons at the LHC and Beyond. *Phys. Rev.*, D76:036006, 2007.

[67] CMS Higgs PAG. List of question for the preapproval checks. `https://twiki.cern.ch/twiki/bin/viewauth/CMS/HiggsWG/HiggsPAGPreapprovalChecks`.

[68] CMS BTV POG. Supported Algorithms and Operating Points. `https://twiki.cern.ch/twiki/bin/viewauth/CMS/BtagRecommendation80XReReco#Supported_Algorithms_and_Operati`.

[69] Albert M Sirunyan et al. Search for resonant and nonresonant Higgs boson pair production in the bblnulnu final state in proton-proton collisions at sqrt(s) = 13 TeV. 2017.

[70] Abdus Salam and John Clive Ward. On a gauge theory of elementary interactions. *Nuovo Cim.*, 19:165–170, 1961.

[71] Steven Weinberg. A model of leptons. *Phys.Rev.Lett.*, 19:1264–1266, 1967.

[72] Albert M Sirunyan et al. Evidence for the Higgs boson decay to a bottom quark-antiquark pair. 2017.

[73] Albert M Sirunyan et al. Particle-flow reconstruction and global event description with the CMS detector. *JINST*, 12(10):P10003, 2017.

[74] Aruna Kumar Nayak. Reconstruction of physics objects in the CMS detector. *PoS*, CHARGED2012:010, 2012.

[75] Lisa Randall and Raman Sundrum. Large mass hierarchy from a small extra dimension. *Phys. Rev. Lett.*, 83:3370–3373, Oct 1999.

[76] Alexandra Oliveira. Gravity particles from Warped Extra Dimensions, predictions for LHC. 2014.

[77] Serguei Chatrchyan et al. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett.*, B716:30–61, 2012.

[78] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett.*, B716:1–29, 2012.

[79] Giuliano Panico. Prospects for double Higgs production. *Frascati Phys. Ser.*, 61:102, 2016.

[80] I. Belotelov, I. Golutvin, D. Bourilkov, A. Lanyov, E. Rogalev, M. Savina, and S. Shmatov. Search for ADD extra dimensional gravity in di-muon channel with the CMS detector. CMS Note 2006/076, 2006.

[81] M. Aldaya, P. Arce, J. Caballero, B. de la Cruz, P. Garcia-Abia, J. M. Hernandez, M. I. Josa, and E. Ruiz. Discovery potential and search strategy for the standard model Higgs boson in the $H \to ZZ^{\star} \to 4\mu$ decay channel using a mass-independent analysis. CMS Note 2006/106, 2006.

[82] A. Brandt et al. Measurements of single diffraction at $\sqrt{s} = 630$ GeV: Evidence for a non-linear $\alpha(t)$ of the pomeron. *Nucl. Phys. B*, 514:3, 1998.

[83] W. Buchmüller and D. Wyler. Constraints on SU(5)-type leptoquarks. *Phys. Lett. B*, 177:377, 1986.

[84] CMS Collaboration. CMS technical design report, volume II: Physics performance. *J. Phys. G*, 34:995, 2007.

[85] CMS Collaboration. Jet performance in pp collisions at $\sqrt{s}$=7 TeV. CMS Physics Analysis Summary CMS-PAS-JME-10-003, 2010.

[86] S. Chatrchyan et al. The CMS experiment at the CERN LHC. *JINST*, 3:S08004, 2008.

[87] Particle Data Group, J. Beringer, et al. Review of Particle Physics. *Phys. Rev. D*, 86:010001, 2012.

[88] ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD Electroweak and Heavy Flavour Groups. Precision electroweak measurements and constraints on the Standard Model. 2010.

[89] I. Bertram, G. Landsberg, J. Linnemann, R. Partridge, M. Paterno, and H. B. Prosper. A recipe for the construction of confidence limits. Technical Report TM-2104, Fermilab, 2000.

[90] L. Moneta, K. Belasco, K. S. Cranmer, A. Lazzaro, D. Piparo, G. Schott, W. Verkerke, and M. Wolf. The RooStats Project. In *13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT2010)*. SISSA, 2010. PoS(ACAT2010)057.

[91] Vardan Khachatryan et al. Search for the standard model Higgs boson produced through vector boson fusion and decaying to $b\bar{b}$. *Phys. Rev.*, D92(3):032008, 2015.

[92] Performance of muon identification in pp collisions at s**0.5 = 7 TeV. Technical Report CMS-PAS-MUO-10-002, CERN, Geneva, 2010.

[93] Serguei Chatrchyan et al. Performance of CMS muon reconstruction in *pp* collision events at $\sqrt{s} = 7$ TeV. *JINST*, 7:P10002, 2012.

[94] CMS COLLABORATION. Particle–flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss}. CMS Physics Analysis Summary CMS-PAS-PFT-09-001, CERN, 2009.

[95] CMS COLLABORATION. Commissioning of the particle-flow event reconstruction with the first lhc collisions recorded in the cms detector. CMS Physics Analysis Summary CMS-PAS-PFT-10-001, CERN, 2010.

[96] Vardan Khachatryan et al. Performance of Electron Reconstruction and Selection with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV. *JINST*, 10(06):P06005, 2015.

[97] CMS Collaboration. Search for pair production of first-generation scalar leptoquarks in pp collisions at $\sqrt{s} = 7$ TeV. Submitted to *Phys. Rev. Lett.*, 2010.

[98] CMS Collaboration. Performance of cms muon reconstruction in pp collision events at $\sqrt{s} = 7\,$TeV. Submitted to *J. Inst.*, 2012.

[99] ATLAS Collaboration. Search for the Higgs boson in the H →WW(*)→ $\ell^+\nu\ell^-\bar{\nu}$ decay channel in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. Submitted to *Phys. Rev. Lett.*, 2011.

[100] Matteo Cacciari and Gavin P. Salam. Dispelling the N^3 myth for the k_t jet-finder. *Phys. Lett. B*, 641:57, 2006.

[101] CMS Luminosity Measurements for the 2016 Data Taking Period. Technical Report CMS-PAS-LUM-17-001, CERN, Geneva, 2017.

[102] CMS Muon POG. Reference muon id, isolation and trigger efficiencies for Run-II. `https://twiki.cern.ch/twiki/bin/viewauth/CMS/MuonReferenceEffsRun2`.

[103] John M. Campbell, R. Keith Ellis, Paolo Nason, and Emanuele Re. Top-pair production and decay at NLO matched with parton showers. *JHEP*, 04:114, 2015.

[104] Ryan Gavin, Ye Li, Frank Petriello, and Seth Quackenbush. FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order. *Comput. Phys. Commun.*, 182:2388, 2011.

[105] Ye Li and Frank Petriello. Combining QCD and electroweak corrections to dilepton production in FEWZ. *Phys. Rev. D*, 86:094034, 2012.

[106] Vardan Khachatryan et al. Event generator tunes obtained from underlying event and multiparton scattering measurements. *Eur. Phys. J. C*, 76(3):155, 2016.

[107] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. A Brief Introduction to PYTHIA 8.1. *Comput. Phys. Commun.*, 178:852–867, 2008.

[108] Rikkert Frederix and Stefano Frixione. Merging meets matching in MC@NLO. *JHEP*, 12:061, 2012.

[109] Simone Alioli, Paolo Nason, Carlo Oleari, and Emanuele Re. NLO single-top production matched with shower in POWHEG: s- and t-channel contributions. *JHEP*, 09:111, 2009. [Erratum: JHEP02,011(2010)].

[110] Michele de Gruttola, Caterina Vernieri, Pierluigi Bortignon, David Curry, Ivan Furic, Jacobo Konigsberg, Sean-Jiun Wang, Paolo Azzurri, Tommaso Boccali, Andrea Rizzi, Silvio Donato, Stephane Brunet Cooperstein , James Olsen, Christopher Palmer, Lorenzo Bianchini, Christoph Grab, Gael Ludovic Perrin, and Luca Perrozzi. Search for the Standard Model Higgs Boson Produced in Association with W and Z and Decaying to Bottom Quarks. `http://cms.cern.ch/iCMS/jsp/db_notes/noteInfo.jsp?cmsnoteid=CMS%20AN-2015/168`.

[111] Michele de Gruttola, Rami Kamalieddin, Ilya Kravchenko, Lesya Shchutska. Search for resonant diHiggs production with bbZZ decays with the 2b2l2nu signature using 35.9/fb data of 2016 pp collisions at the LHC. `http://cms.cern.ch/iCMS/jsp/openfile.jsp?tp=draft&files=AN2017_198_v17.pdf`.

[112] Chris Palmer. VHbb Electron Trigger and ID+ISO SFs for 2016 data. `https://indico.cern.ch/event/604949/contributions/2543520/attachments/1439974/2216426/VHbb_TnP_SFs_egamma_april.pdf#search=vhbb%20AND%20cerntaxonomy%3A%22Indico%2FExperiments%2FCMS%20meetings%2FPH%20%2D%20Physics%2FEgamma%22`.

[113] CMS JetMET group. Jet Energy Resolution. https://twiki.cern.ch/twiki/bin/viewauth/CMS/JetResolution.

[114] CMS MET group. MET Corrections and Uncertainties for Run-II. https://twiki.cern.ch/twiki/bin/viewauth/CMS/MissingETRun2Corrections.

[115] CMS MET group. MET Filter Recommendations for Run II. https://twiki.cern.ch/twiki/bin/view/CMS/MissingETOptionalFiltersRun2.

[116] CMS EGM POG. Multivariate Electron Identification for Run2. https://twiki.cern.ch/twiki/bin/viewauth/CMS/Multivari\ateElectronIdentificationRun2.

[117] Helge Voss, Andreas Höcker, Jörg Stelzer, and Frerik Tegenfeldt. TMVA, the toolkit for multivariate data analysis with ROOT. In *XIth International Workshop on Advanced Computing and Analysis Techniq ues in Physics Research (ACAT)*, page 40, 2007.

[118] CMS Higgs WG. Documentation of the RooStats -based statistics tools for Higgs PAG. https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideHiggsAnalysisCombinedLimit.

[119] CMS Higgs WG. Binned shape analysis with the Higgs Combination Tool. https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideHiggsAnalysisCombinedLimit#Binned_shape_analysis.

[120] bbbb team. Search for resonant pair production of Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at 13 TeV. http://cms.cern.ch/iCMS/analysisadmin/get?analysis=HIG-17-009-pas-v5.pdf.

[121] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. The anti-k_t jet clustering algorithm. *JHEP*, 04:063, 2008.

[122] Torbjörn Sjöstrand, Stephen Mrenna, and Peter Skands. PYTHIA 6.4 physics and manual. *JHEP*, 05:026, 2006.

[123] C. Giunti and M. Laveder. Neutrino mixing. In F. Columbus and V. Krasnoholovets, editors, *Developments in Quantum Physics*. Nova Science Publishers, Inc., 2004.

[124] M. Della Negra, P. Jenni, and T. S. Virdee. Journey in the search for the higgs boson: The atlas and cms experiments at the large hadron collider. *Science*, 338(6114):1560–1568, 2012.

[125] Matthias U. Mozer. Electroweak Physics at the LHC. *Springer Tracts Mod. Phys.*, 267:1–115, 2016.

[126] Roger Wolf. *The Higgs Boson Discovery at the Large Hadron Collider*, volume 264. Springer, 2015.

[127] Steven Weinberg. The Making of the Standard Model. *Eur. Phys. J. C*, 34(hep-ph/0401010):5–13. 21 p. ; streaming video, 2003.

[128] Jose Andres Monroy Montanez, Kenneth Bloom, and Aaron Dominguez. Search for production of a Higgs boson and a single Top quark in multilepton final states in pp collisions at $\sqrt{s} = 13$ TeV, Jul 2018. Presented 23 Jul 2018.

[129] Albert M Sirunyan et al. Search for Higgs boson pair production in the $\gamma\gamma \mathrm{b}\overline{\mathrm{b}}$ final state in pp collisions at $\sqrt{s} = 13$ TeV. 2018.

[130] Lisa Randall and Raman Sundrum. A Large mass hierarchy from a small extra dimension. *Phys. Rev. Lett.*, 83:3370–3373, 1999.

[131] Kunihito Uzawa, Yoshiyuki Morisawa, and Shinji Mukohyama. Excitation of Kaluza-Klein gravitational mode. *Phys. Rev.*, D62:064011, 2000.

[132] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo. Phenomenology of the Randall-Sundrum Gauge Hierarchy Model. *Phys. Rev. Lett.*, 84:2080, 2000.

[133] Michael Forger and Hartmann Romer. Currents and the energy momentum tensor in classical field theory: A Fresh look at an old problem. *Annals Phys.*, 309:306–389, 2004.

[134] Chuan-Ren Chen and Ian Low. Double take on new physics in double Higgs boson production. *Phys. Rev.*, D90(1):013018, 2014.

[135] Roberto Contino, Margherita Ghezzi, Mauro Moretti, Giuliano Panico, Fulvio Piccinini, and Andrea Wulzer. Anomalous Couplings in Double Higgs Production. *JHEP*, 08:154, 2012.

[136] Gennadi Sardanashvily. *Noether's theorems: applications in mechanics and field theory.* Atlantis studies in variational geometry. Springer, Paris, 2016.

[137] Thomas Schörner-Sadenius. *The Large Hadron Collider: harvest of run 1.* Springer, Cham, 2015.

[138] CERN. *Large Hadron Collider in the LEP Tunnel*, Geneva, 1984. CERN.

[139] Lyndon R Evans and Philip Bryant. LHC Machine. *JINST*, 3:S08001. 164 p, 2008. This report is an abridged version of the LHC Design Report (CERN-2004-003).

[140] Karsten Eggert, K Honkavaara, and Andreas Morsch. Luminosity considerations for the LHC. Technical Report CERN-AT-94-04-DI. CERN-LHC-Note-263. LHC-NOTE-263, CERN, Geneva, Feb 1994.

[141] Oswald Gröbner. The LHC Vacuum System. (LHC-Project-Report-181. CERN-LHC-Project-Report-181):5 p, May 1998.

[142] Wolfgang Adam, R Frühwirth, Are Strandlie, and T Todor. Reconstruction of Electrons with the Gaussian-Sum Filter in the CMS Tracker at the LHC. Technical Report CMS-NOTE-2005-001, CERN, Geneva, Jan 2005.

[143] Thomas Lenzi. Development and Study of Different Muon Track Reconstruction Algorithms for the Level-1 Trigger for the CMS Muon Upgrade with GEM Detectors. Master's thesis, U. Brussels (main), 2013.

[144] Prospects for HH measurements at the HL-LHC. Technical Report CMS-PAS-FTR-18-019, CERN, Geneva, 2018.

[145] Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV. Technical Report CMS-PAS-HIG-17-030, CERN, Geneva, 2018.

[146] The CMS collaboration. Missing transverse energy performance of the cms detector. *Journal of Instrumentation*, 6(09):P09001, 2011.