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

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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.

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This will be a long list!

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Chapter *1*

Physics Object Reconstruction

Excellent spatial resolution of the CMS trackers, high granularity of the calorimeters, and almost 4π coverage of the detector, allowed the CMS to introduce the particle flow (PF) algorithm [**?**] for a global event reconstruction. PF takes the input from all subdetectors, analyses the redundant information, removes the duplicate one, and forms the physics objects. PF procedure starts with identification of tracks and calorimeter clusters, then the reconstruction of the physics objects is performed, such as electrons, muons, jets, etc. In this section we will discuss the whole PF approach and all key elements of this reconstruction sequence.

1.1 Track Reconstruction

The reconstruction starts with the clusters of signals ("hits") in the inner tracker. The information from these clusters in the Pixel and Strip subdetectors is aggregated based on their signal-to-noise ratios. The charge-weighted averaging is performed (for different particle charge hypothesis), as well as other corrections are further applied to identify the real hit positions.

The helix trajectory that the particle follows in the magnetic field inside of the detector is characterised by five parameters: the direction in η, the 3D position with respect to the reference point, which is the centre of the IP, and the curvature of the track with the radius R. This information is enough to compute estimates of basic physics quantities, however, the this task is complicated by the presence of event high multiplicity (number of charged particles produced in the same event) and also by the physics aspect of the electron propagation in matter: an electron traversing the detector has nearly 85 % probability to emit a bremsstrahlung photon. Hadronic effects also need to be taken into account: a hadron has a 20 % probability to experience multiple scattering on the nuclei of the detector before reaching the HCAL.

To keep the track finding efficiency high, while maintaining low the efficiency of miss-identified tracks, track reconstruction is performed sequentially using the combinatorial track finder (CTF) [**?**]. First the "purest" tracks are reconstructed, they have high p_T and the hits point towards the primary vertex (PV). The term PV is used to refer to the vertex which is the actual point of origin of the produced particle, when several other hard scattering vertices are present in the event. Then these pure tracks are removed from the collection of tracks and another round of the track reconstruction starts. This procedure applied several times reduces the combinatorial factor and also simplifies the identification of tracks with the low p_T or those which do not point to the PV. During each iteration, the reconstruction follows these steps:

- Seed generation. Rough estimates of the particle trajectories ("seeds") are produced using either three hits or two hits and a PV constraint. Based on which iteration the algorithm is at, some additional constraints are applied, e.g., a minimal p_T requirement, the need for the seed to originate close to the beam spot, etc.

- Trajectory building. Initial seeds are projected towards the compatible hits in the next layers based on the Kalman Filter (KF) procedure [**?**]. The extrapolation is done until the outermost layer of the tracker is reached or when a "terminating condition" is satisfied, e.g., when the iteration accumulated the maximum number of invalid hits ("fake hits"). Each obtained trajectory is updated using a KF approach based on the compatibility of hits to form a better track candidate. The procedure is complicated by the fact that the same initial seed can give rise to several track candidates or vice versa, the same track candidate may be compatible with different seeds. Additionally, the trajectory building step should take into account energy loses of the particle due to multiple scattering on the detector material, inhomogeneities of the tracker material, and the effects of the regions of non constant magnetic field.

- Track fitting. After the track candidate has been built, the track parameters are refitted by a KF and the "smoother". This step uses the full available information about the track and gives optimal estimates of the track parameters. To remove a large number of fake tracks, which are present due to a very complicated nature of the problem and the high track multiplicity in the event, a multivariate (MVA) selection is applied. MVA incorporates variables that discriminate real tracks from the fakes: the signed transverse curvature and impact parameters (with respect to the beam spot), the polar and azimuthal angles, number of missing hits, the fit quality variables, etc.

The CTF procedure runs for 10 iterations. For 2016 collisions with a mean pileup (additional hard scattering vertices) of 24, the CTF efficiency to identify real tracks varied from 80 to 95% with the mis-identification efficiency of 5 - 10 %.

1.1.1 Muon tracking

Muons are detected by the inner tracker and also by the outer (muon) tracker. This greatly improves muon track reconstruction and motivated the development of a dedicated muon reconstruction algorithms. The ninth and the tenth iterations of the CTF are focused on the muon reconstruction. These iterations are using three separate algorithms to identify:

- Standalone muons. This algorithms uses only muon tracker information: DTs, CSCs, RPCs. Hits from the inner chambers are used as seeds and projected to hits in the outer chambers. Then, a standard KF procedure is used to identify track candidates, which are called standalone muons.

- Tracker muons. Only the inner tracking information is used to form tracks. Tracks are further projected to muon subsystems, where a compatibility with at least one muon hit is required. This algorithm works with low momentum muons: tracks with p_T above 0.5 GeV and a total momentum greater than 2.5 GeV.

- Global muons. Tracker tracks and standalone tracks are projected to the outermost layer of the muon system, checking the compatibility between two approaches. The resulting combined set of track hits is refitted to produce a global muon track. Mostly high momentum muons with $p_T >$?? 200 GeV profit from this algorithm.

1.1.2 Electron tracking

Electrons are also detected by the inner tracker, however, their reconstruction is complicated by the fact that they emit bremsstrahlung photons and the trajectory becomes more complex. As a result, the clustering algorithms need also to identify the bremsstrahlung photons and account for the fact that the energy clusters corresponding to these photons may be located outside of the main electron trajectory, when extrapolated to the ECAL.

Since a KF approach assumes that energy losses are Gaussian, and this is not the case for electrons, a dedicated procedure is developed - a modified KF - the Gaussian Sum Filter (GSF) [144]. In this method the radiated energy losses are approximated by the sum of Gaussian distributions.

The electron seeds for the GSF are built using the ECAL information. Two different approaches are developed for the track reconstruction:

- Super Cluster based electrons. Cluster of energy in the ECAL and grouped together to form super clusters (SCs). Using the information of the energy spread among the clusters, the curvature of the electrons is estimated and tracker seeds are formed, with the SC position as a constraint.

- Tracks based electrons. Tracks from the inner tracker are projected to ECAL clusters, checking the compatibility using quality variables, such as χ^2, number of missing hits (absent hits along the path of the track), etc.

A typical momentum resolution for electrons in $Z \to e^- e^+$ decays is approximately 1.7 - 4.5%.

Primary vertex finding Reconstructed tracks can be used to identify primary vertices, i.e. the locations of all proton-proton interactions in the event. These include the vertex corresponding to the ?hard? interaction, used for physics analysis and hereafter referred to as the primary vertex (PV), as well as additional parasitic interactions (pileup). The primary vertices are used to measure the position and size of the beam spot, i.e. the 3-D distribution of the luminous region, which feeds back into the track reconstruction sequence (both online and offline) as it is used as a constraint on track origin in some CTF iterations. Identifying pileup vertices is also of fundamental importance to mitigate the effect of pileup on object reconstruction performance, as will be described in Sec. 2.3.8. Lastly, knowledge of the position of the primary vertex is a crucial ingredient for b tagging (see Sec. 2.3.7). Vertex reconstruction consists of selecting a subset of tracks using quality criteria, and clustering them based on the z-coordinate of their PCA to the centre of the beam spot. To efficiently resolve close-by interactions while avoiding to split clusters corresponding to genuine vertices, the clustering is based on a deterministic annealing algorithm, seeking the global minimum of an analogue of free energy through step-wise reductions of the ?temperature? T. At infinite T, all tracks are assigned to a single vertex. As T is reduced, the vertices are allowed to split if the resulting configuration is more favoured. Once the minimum is reached, vertices containing at least two tracks are fitted to estimate their position. The resolution on vertex position varies from 10 ?m to 100 ?m, depending on the number and pT of the clustered tracks [195]. Finally, the beam spot can be measured by fitting the distribution of reconstructed vertices, a procedure repeated for every LS in the data. To pinpoint the vertex corresponding to the hard interaction in the event, objects are built, for each vertex candidate, using a jet clustering algorithm taking as input all the tracks associated to the vertex, as well as the vertex? missing transverse momentum. The ??2 vertex with the highest pT, where the sum runs over the thus defined objects, is taken to be the hard interaction vertex. 2.3.2. Calorimeter clusters and particle-flow links In the PF algorithm, the calorimeters primarily serve to identify and measure neutral hadrons and photons, help in the reconstruction of electrons, and improve the energy measurement for charged hadrons (in particular at high pT). The clustering of energy deposits used in PF was specifically designed to resolve individual particles. Local cell energy maxima, above a certain threshold, define cluster seeds. Contiguous deposits are merged with the seeds, forming topological clusters. The procedure is carried out independently for each subdetector (ECAL, HCAL and HF) and partition (barrel and endcaps). Within a topological cluster, to take into account the overlap of energy deposits due to individual particles, clusters are identified using a Gaussian-mixture model, where the number of Gaussian energy deposits corresponds to the number of seeds, and the position and amplitude of each Gaussian are the cluster parameters. The single-particle PF response needs to be carefully calibrated, to correct i.a. for threshold effects and for the nonlinearity of the detector response. This calibration is carried out using simulated data, separately for photons using only the ECAL, and for neutral hadrons, which deposit

energy sometimes in both the ECAL and the HCAL, sometimes mostly in the HCAL. To identify individual particles in the events, the PF approach relies on information from the different subdetectors. To that end, the link algorithm combines PF elements (tracks, clusters) to create PF blocks, which form the basis for the different object reconstruction algorithms. For instance, an inner track is linked with a calorimeter cluster if it can be extrapolated to a position compatible with that of the cluster. Further, if tangents to a GSF track can be extrapolated to ECAL clusters, these clusters can be linked with the track to recover bremsstrahlung photons. Pairs of tracks compatible with originating +? from a photon conversion into an e e pair also become linked. Similarly, groups of track are formed for reconstructed nuclear interactions within the tracker volume. Links between calorimeter clusters are only formed out of the tracker acceptance, when ECAL clusters are contained within the envelope of HCAL clusters. Lastly, as already hinted at in Sec. 2.3.1, links between inner tracks and muon tracks or segments establish global or tracker muons, respectively. With all the possible blocks in hand, object identification proceeds in steps. PF blocks corresponding to the candidates reconstructed at a given step are masked, and not considered further.

- somewhere a section on physics objects where you discuss that there are tracks, there are jets, there are b-jets, what it means an isolated lepton, what it means missing momentum, and so forth. For example, Ekaterina has a section on particle flow, if I remember right, where she discusses that. Or you can have a section that just discuses the proton-proton collisions environment and explains that many particles created in collisions are unstable and decay right away. What is observable in an experiment such as CMS is longer-lived or stable particles. These include electrons, muons, photons, and some ground state hadrons. At the same time, energetic quarks or gluons hadronize and can be seen in a particle detectors as jets of hadrons (so define jets here). Same for tau leptons, we detect them either as electrons/muons, or hadronic jets. Etc. If you have such a conceptual paragraph here, some time later you can have a particle flow discussion when it is time to be more specific. But discussion at this level above would allow you to then discuss the requirements on CMS design using terms like b-jets or isolated leptons.

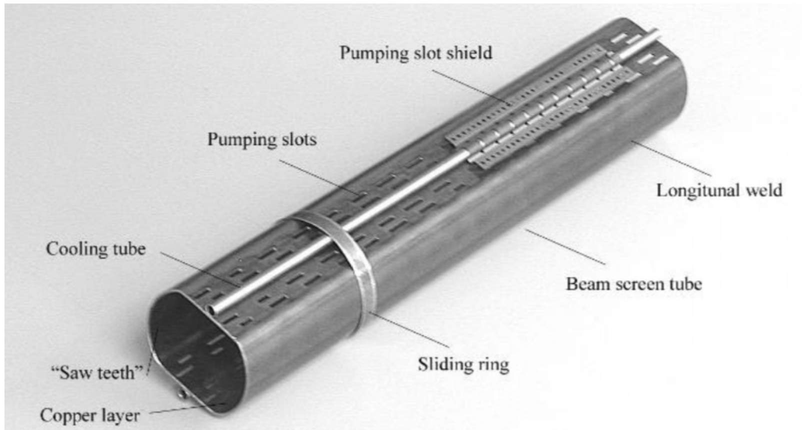

Figure 1.1: Beam screen.

EGAMMA AT LEAST SAY THAT HAS BEEN WORKING AND SHOW SOME PLOTS?

References

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

[2] 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.

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

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

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

[6] Carl Bender. Mathematical physics.

[7] 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.

[8] 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.

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

[10] Eric W. Weisstein. Fundamental forces.

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

[12] Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler. *Gravitation / Charles W. Misner, Kip S. Thorne, John Archibald Wheeler.* W. H. Freeman San Francisco, 1973.

[13] 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.

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

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

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

[17] 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.

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

[19] R. P. Feynman. The theory of positrons. *Phys. Rev.*, 76:749–759, Sep 1949.

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

[21] S. L. Glashow. Partial Symmetries of Weak Interactions. *Nucl. Phys.*, 22:579–588, 1961.

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

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

[24] 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.

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

[26] 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.

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

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

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

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

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

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

[33] 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.

[34] Peisi Huang, Aniket Joglekar, Min Li, and Carlos E. M. Wagner. Corrections to di-Higgs boson production with light stops and modified Higgs couplings. *Phys. Rev.*, D97(7):075001, 2018.

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

[36] 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.

[37] 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.

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

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

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

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

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

[43] 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.

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

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

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

[47]

[48] 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.

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

[50] 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)].

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

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

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

[54] 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.

[55] Comparison of nuisances for background only case, 350 GeV mass hypothesis. http://rkamalie.web.cern.ch/rkamalie/feb12/Comparison_of_nuisances_expectedSignal0_35

[56] Comparison of nuisances for s+b case, 350 GeV mass hypothesis. http://rkamalie.web.cern.ch/rkamalie/feb12/Comparison_of_nuisances_expectedSignal1_35

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

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

[59] Standard Model Cross Sections for CMS at 13 TeV. https://twiki.cern.ch/twiki/bin/viewauth/CMS/StandardModelCrossSectionsat13TeVInclusi

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

[61] NNLO+NNLL top-quark-pair cross sections. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO#Top_quark_pair_cross_se

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

[63] CMS GEN XSEC Task Force. https://twiki.cern.ch/twiki/bin/viewauth/CMS/GenXsecTaskF

[64] SM Higgs Branching Ratios and Total Decay Widths (update in CERN Report4 2016). https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR#Higgs_2_g

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

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

[67] 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.

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

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

[70] 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.

[71] 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.

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

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

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

[75] 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`.

[76] 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`.

[77] 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.

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

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

[80] 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.

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

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

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

[84] 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.

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

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

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

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

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

[90] 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.

[91] 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.

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

[93] 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.

[94] 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.

[95] 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.

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

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

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

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

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

[101] 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.

[102] 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.

[103] 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.

[104] 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.

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

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

[107] 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.

[108] 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.

[109] 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.

[110] 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.

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

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

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

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

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

[116] 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.

[117] 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.

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

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

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

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

[122] 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)].

[123] 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`.

[124] 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`.

[125] 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`.

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

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

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

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

[130] 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.

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

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

[133] 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.

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

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

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

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

[138] 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.

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

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

[141] 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).

[142] 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.

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

[144] 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.

[145] 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.

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

[147] 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.

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

[149] Search for resonant double Higgs production with $bbZZ$ decays in the $b\bar{b}\ell\ell\nu\nu$ final state. Technical Report CMS-PAS-HIG-17-032, CERN, Geneva, 2018.

[150] Werner Herr and B Muratori. Concept of luminosity. 2006.

[151] Charles W. Misner, K. S. Thorne, and J. A. Wheeler. *Gravitation*. W. H. Freeman, San Francisco, 1973.

[152] Cecile Noels. Literature in focus - The Large Hadron Collider: A Marvel of Technology. Literature in focus - The Large Hadron Collider: A Marvel of Technology. (BUL-NA-2009-414. 51/2009):11, Dec 2009.

[153] John Hauptman. *Particle physics experiments at high energy colliders*. 2011.

[154] CMS Collaboration. The Phase-2 Upgrade of the CMS Tracker. Technical Report CERN-LHCC-2017-009. CMS-TDR-014, CERN, Geneva, Jun 2017.

[155] Philippe Bloch, Robert Brown, Paul Lecoq, and Hans Rykaczewski. *Changes to CMS ECAL electronics: addendum to the Technical Design Report*. Technical Design Report CMS. CERN, Geneva, 2002.

[156] *The CMS hadron calorimeter project: Technical Design Report*. Technical Design Report CMS. CERN, Geneva, 1997.

[157] G Baiatian, Albert M Sirunyan, Virgil E Emeliantchik, Igor Barnes, Alvin T Laasanen, and Arnold Pompos. Design, Performance, and Calibration of CMS Hadron-Barrel Calorimeter Wedges. Technical Report CMS-NOTE-2006-138. 1, CERN, Geneva, May 2007.

[158] G L Bayatian, S Chatrchyan, H Hmayakyan, A Poblaguev, M E Zeller, and B S Yuldashev. *CMS Physics: Technical Design Report Volume 1: Detector Performance and Software*. Technical Design Report CMS. CERN, Geneva, 2006. There is an error on cover due to a technical problem for some items.

[159] CMS Collaboration. The Phase-2 Upgrade of the CMS Muon Detectors. Technical Report CERN-LHCC-2017-012. CMS-TDR-016, CERN, Geneva, Sep 2017. This is the final version, approved by the LHCC.

[160] G. Bauer et al. The CMS data acquisition system software. *J. Phys. Conf. Ser.*, 219:022011, 2010.

[161] Vardan Khachatryan et al. The CMS trigger system. *JINST*, 12(01):P01020, 2017.