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 A Toroidal LHC ApparatuS (ATLAS) and The Compact Muon Solenoid (CMS), most of the quantum mechanical properties that describe the long-awaited Higgs boson have been measured. Due to an impeccable work of the LHC, dozens of fb^{-1} of data have been delivered to both experiments. Finally, it became possible for analyses that have a very low cross section to observe rare decay modes of the Higgs boson, as was done successfully recently in ttH and VHbb channels. The only untouched territory is a double Higgs boson production. Data will not help us much either at the HL-LHC, the process will remain unseen even in the most optimistic scenarios, so one has to rely solely on new reconstruction methods as well as new analysis techniques. This thesis is addressing both goals. I have been blessed by an opportunity to work in the CMS electron identification group, where we have developed new electron identification algorithms. The majority of this thesis, however, will be devoted to the second goal of HL-LHC. We establish the techniques for the first ever analysis at the LHC that searches for the double Higgs 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 analysis 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. Both spin scenarios of the resonance are considered: spin 0 (later called "graviton") and spin 2 (later called "radion"). In the absence of the

evidence of the resonant double Higgs boson production from the previous searches, we set upper confidence limits. When combined with other search channels, this analysis will contribute to the discovery of the double Higgs production and we would be able to finally probe the Higgs boson potential using its self-coupling.

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

Lenin, 1922.

ACKNOWLEDGMENTS

This will be a longggggg list!

Table of Contents

List of Figures

List of Tables

Chapter *1*

Theoretical approach

1.1 The Standard Model

The SM uses the Lagrangian formalism to describe the interactions of elementary particles and fields. The SM Lagrangian can be split into four main terms [1]:

- Gause bosons and their interactions
- Fermions and their interactions with the gauge bosons
- Higgs boson, its self-interaction, and interaction with the gauge bosons to give them mass, which is not possible solely by the $\mathcal{L}_{YM}$
- Fermions and their interactions with the Higgs boson, which through the Yukawa mechanism gives mass to fermions

or equivalently:

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_{ferm} + \mathcal{L}_{H} + \mathcal{L}_{Yuk} \tag{1.1}$$

The first term in the SM Lagrangian:

$$\mathcal{L}_{YM} = -\frac{1}{4}W^i_{\mu\nu}(x)W_i^{\mu\nu}(x) - \frac{1}{4}B_{\mu\nu}(x)B^{\mu\nu}(x) - \frac{1}{4}G^a_{\mu\nu}(x)G_a^{\mu\nu}(x) \tag{1.2}$$

where

$$B_{\mu\nu}(x) \equiv \partial_\mu B_\nu - \partial_\nu B_\mu \tag{1.3}$$

$$W^i_{\mu\nu}(x) \equiv \partial_\mu W^i_\nu(x) - \partial_\nu W^i_\mu(x) - g\varepsilon^{ijk} W^j_\mu W^k_\nu \tag{1.4}$$

$$G^a_{\mu\nu}(x) \equiv \partial_\mu G^a_\nu(x) - \partial_\nu G^a_\mu(x) - g_s f^{abc} G^b_\mu G^c_\nu \tag{1.5}$$

$$\tag{1.6}$$

with $i, j, k = 1, 2, 3$ and $a, b, c = 1, ..., 8$. The fields have the following connections to their underlying symmetries: $B_{\mu\nu}$ corresponds to $U(1)$ symmetry of the weak hypercharge Y_k and "B" term is simply a kinematic term while "W" and "G" terms describe interactions among the corresponding bosons, where $W^i_{\mu\nu}$ corresponds to $SU(2)_I$ symmetry of the weak isospin I^i_w, and $G^a_{\mu\nu}$ corresponds to $SU(3)_c$ symmetry of the QCD color charge. g and ε are $SU(2)$ coupling and structure constants, while g_s and f are coupling and structure constants for $SU(3)$.

The next term in the SM Lagrangian shows how fermions interact with the gauge bosons. Notice, that the mass terms are still absent:

$$\mathcal{L}_{ferm} = i\bar{\Psi}_L \not{D} \Psi_L + i\bar{\psi}_{l_R} \not{D} \psi_{l_R} + i\bar{\Psi}_Q \not{D} \Psi_Q + i\bar{\psi}_{u_R} \not{D} \psi_{u_R} + i\bar{\psi}_{d_R} \not{D} \psi_{d_R} \tag{1.7}$$

Above Ψ represents a doublet of a charged lepton and a corresponding neutral lepton within the same lepton family of $SU(2)_L$, a letter Q is reserved for a family of quarks, and ψ_R describes a right-handed leptonic singlet.

Gauge bosons interactions are present due to the derivative term:

$$D_\mu = \partial_\mu + igI^i_w W^i_\mu + ig' Y_w B_\mu + ig_s T^a_c G^a_\mu \tag{1.8}$$

$$\tag{1.9}$$

Physical fields in this notation are represented by a linear combination of W and B fields:

$$
\begin{aligned}
A_\mu =& B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W \\
Z_\mu =& - B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W
\end{aligned}
\tag{1.10}
$$

where θ_W is known as the *Weinberg angle* [2].

These two first terms of the SM Lagrangian is enough to have a theory of fermions and bosons, but they have no mass [3]. As discussed before, to ensure that weak bosons are massive, we need a Higgs term. Higgs mechanism enters the SM Lagrangian through the corresponding Higgs Lagrangian term given by

$$
\mathcal{L}_H = (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi), \qquad V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 \tag{1.11}
$$

where

$$
\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 = (v + H + i\chi)/\sqrt{2} \end{pmatrix} \quad \text{and} \quad v = 2\sqrt{\frac{\mu^2}{\lambda}} \tag{1.12}
$$

Here μ and λ are parameters of the Higgs potential. The discovery of the Higgs boson and the measurement of its mass studies the μ parameter, double Higgs boson non-resonant searches target λ parameter to know more precisely what is the shape of Higgs potential. After the SSB, the value of the Higgs field vacuum expectation value can be expressed in term of μ and λ and is usually denoted by v [4].

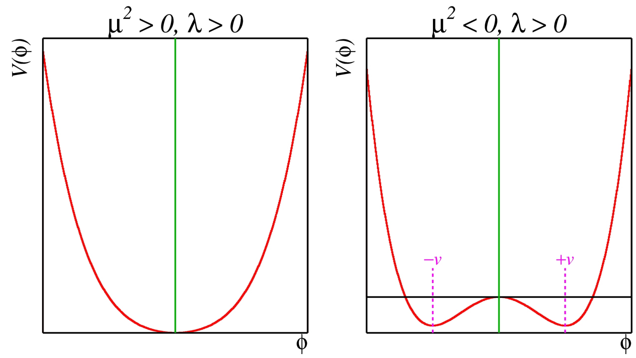

Figure 1.1: Shape of the Higgs potential before and after SSB that is determined at the leading orders by μ and λ parameters.

I After adding $\mathcal{L}_H$ and rearranging term, bosons have masses given by:

$$M_W = \frac{gv}{2}, \quad M_Z = \frac{M_W}{\cos\theta_W}, \quad M_H = \sqrt{2\mu^2} \tag{1.13}$$

The final piece of the SM Lagrangian is the Yukawa term, which Lagrangian is given by:

$$\mathcal{L}_{Yuk} = -i\bar{\Psi}_L G_l \psi_{l_R}\Phi - i\bar{\Psi}_Q G_u \psi_{u_R}\tilde{\Phi} - i\bar{\Psi}_Q G_d \psi_{d_R}\Phi + h.c. \tag{1.14}$$

where $\tilde{\Phi} = i\sigma^2\Phi^*$

The masses of fermions enter the equation through the 3×3 matrices G, which are not known from the theory and are the parameters of the SM. The mass of the fermion is proportional to the Yukawa coupling of the corresponding fermion to the Higgs boson, which has already been mentioned when we discussed the Fig. **??**.

1.2 Beyond the Standard Model

Several BSM theories [5–7] predict a resonant production of the double Higgs boson events through a heavy narrow width resonance ($\sim O(1-10)$ GeV), which could be spin 0 or spin 2 particle [8]. In this particular analysis data is compared with respect to predictions from the Warped Extra Dimensions theory (WED) [9]. WED theory addressing the hierarchy problem adds additional fifth dimension to the 4-dimensional (4D) space-time. In the framework that Randall and Sundrum (RS) [10] followed 4D space then is nothing but an EFT approximation, where the radion or graviton may exist as Kaluza-Klein (KK) [11] excitation modes at the TeV scale. Since LHC had provided us with no evidence of the SM particles interacting with the additional RS dimensions, it is postulated that they are confined to 3-brane, or a wall. At the same time, gravity, which is not in the SM, can propagate freely in the full higher-dimensional space, so-called bulk. If/when the bulk is compactified, it may produce KK modes of the gravitons. In this analysis RS model with parameter k of the order of Planck scale and $\bar{M}_{Pl}$, a reduced 4D M_{Pl} which is a function of the 5D Planck scale M and a parameter k with $k < M$, are assumed to satisfy the constraint $0.01 \leq k/\bar{M}_{Pl} \leq 1$, because values outside of this range are not applicable/or complicate the theory [12]. Considered in this search graviton and radion are thus RS KK graviton and RS radion particles that emerge in RS scenario with a mass of KK state of the order of TeV.

Lagrangian energy stress tensor over fields i [13]

$\lambda_W \sim O(\text{TeV})$

References

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

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

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

[4] 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.

[5] 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.

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

[7] 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.

[8] 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.

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

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

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

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

[13] 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.

[14] 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.

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

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

[17] 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.

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

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

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

[21] 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.

[22] 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.

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

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

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

[26] Hanoch Gutfreund and Jürgen 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.

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

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

[29] Eric W. Weisstein. Fundamental forces.

[30] Carl Bender. Mathematical physics.

[31] 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.

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

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

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

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

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

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

[38] 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.

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