The Compact Muon Solenoid Experiment
Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

08 June 2019 (v2, 05 August 2021)

Search for vector boson fusion production of a massive resonance decaying to a pair of Higgs bosons in the four b quark final state at the HL-LHC using the CMS Phase 2 detector

Lata Panwar for the CMS Collaboration

Abstract

The search for a massive resonance produced by vector boson fusion and decaying into a pair of Higgs bosons, each decaying to a b quark-antiquark pair, at the High Luminosity Large Hadron Collider in proton-proton collisions at a center-of-mass energy of 14 TeV is explored. The Higgs bosons are required to be sufficiently Lorentz-boosted for each to be reconstructed using a single large-area jet. We study the signal sensitivity for a narrow bulk graviton in extradimensional scenarios using a simulation of the upgraded CMS detector, assuming multiple proton-proton collisions in the same bunch crossing (up to 200), for data corresponding to an integrated luminosity of 3 ab^{-1} . The expected significance for different assumed masses of the bulk graviton is presented.

Presented at *DAE-HEP 2018 XXIII DAE-BRNS High Energy Physics Symposium*

Search for vector boson fusion production of a massive resonance decaying to a pair of Higgs bosons in the four b quark final state at the HL-LHC using the CMS Phase-2 detector

on behalf of the CMS collaboration

Alexandra Carvalho¹⁾, Jyothsna Rani Komaragiri²⁾, Devdatta Majumder³⁾, Lata Panwar²⁾

¹⁾*Estonian Academy of Sciences, Tallinn, Estonia,* ²⁾*Indian Institute of Science, India,*

³⁾*University of Kansas, USA*

Abstract. The search for a massive resonance produced by vector boson fusion and decaying into a pair of Higgs bosons, each decaying to a b quark-antiquark pair, at the High Luminosity Large Hadron Collider in proton-proton collisions at a centre-of-mass energy of 14 TeV is explored. The Higgs bosons are required to be sufficiently Lorentz-boosted for each to be reconstructed using a single large-area jet. We study the signal sensitivity for a narrow bulk graviton in extradimensional scenarios using a simulation of the upgraded CMS detector, assuming multiple proton-proton collisions in the same bunch crossing (up to 200), for data corresponding to an integrated luminosity of 3 ab⁻¹. The expected significance for different assumed masses of the bulk graviton is presented.

Keywords: Standard Model, CMS, ATLAS, Higgs boson, Significance, HL-LHC, CERN

Introduction:

The discovery of the Standard Model (SM) Higgs Boson in 2012, from data collected with CMS and ATLAS detector at CERN, Switzerland, has proven the Standard Model the most successful theory of the particle physics. The spontaneous symmetry breaking in the electroweak sector of the SM explains the Higgs boson's existence and how Standard Model particles acquire masses. However, the SM has also shortcomings. It fails to provide a solution for e.g. the hierarchy problem, Gravity, Dark Matter, neutrino oscillation etc. Then we start exploring the physics beyond the SM (BSM).

Several BSM scenarios predict the existence of resonances decaying to a pair of Higgs bosons, such as Warped Extra Dimensional (WED) model [1], which has a spin-0 Radion and a spin-2 first Kaluza-Klein (KK) excitation of the graviton. These resonances may have a significant branching fraction to decay in a Higgs pair.

The search for KK graviton (X) in Vector Boson Fusion (VBF) production mode, as shown in Figure 1, has not yet been explored. While the s-channel production cross section of a bulk graviton, assuming $\kappa/\bar{M}_{\text{pi}} = 0.5$, is in the range 0.05–5 fb for masses between 1.5 and 3 TeV, the VBF production mode is expected to have a cross section an order of magnitude smaller than s-channel. The results published for s-channel [2] shows the negligible production rate of the signal which indicates highly suppressed couplings of X with the SM quarks and gluons. This makes VBF the dominant production process in pp collisions. Thus VBF production mode is interesting to study with large amount of data collected at the high luminosity LHC (HL-LHC).

Figure 1: The vector boson fusion production of a resonance X decaying to a pair of Higgs bosons, where both Higgs bosons decay into 4b final state

In this report, we study the VBF production of WED spin-2 graviton resonance, which decays to pair of Higgs bosons, with 4b quarks in the final state, at the HL-LHC with the upgraded CMS detector.

A simulation [3] of the upgraded Phase-2 CMS detector was used for this study. The signal events for bulk graviton were simulated at leading order using MADGRAPH5_aMC@NLO [4], for masses in the range 1.5 to 3 TeV and for a fixed width of 1% of the mass. The main background is given by multijet events, and has been simulated using PYTHIA8 [5], for events containing two hard partons, with the invariant mass of the two partons is required to be greater than 1 TeV.

Analysis strategy:

For a very massive resonance, highly Lorentz-boosted Higgs bosons are more efficiently reconstructed as a single large-area jet (Higgs jet). In addition, a signal event will also have two energetic jets at large pseudorapidity η . Thus there are two sets of event selections, a) Higgs Jets selection, b) VBF Jets selection.

For a), the two leading- p_T large-radius anti- k_T jets with a distance parameter of 0.8 (AK8 [6]) in the event, J1 and J2, are required to have $p_T > 300$ GeV and $|\eta| < 3.0$. To identify the two leading- p_T AK8 jets with the boosted $H \rightarrow b\bar{b}$ candidates from the $X \rightarrow HH$ decay, these jets are groomed to remove soft and wide-angle radiation effect using the soft-drop mass algorithm [7]. By undoing the last stage of the jet clustering, one gets two subjets each for J1 and J2. The invariant mass of the two subjets is the soft-drop mass of each AK8 jet, which has a distribution with a peak near the Higgs boson mass $m_H = 125$ GeV. The soft-drop mass window selection was optimised using a figure of merit of $S/\sqrt{B}$ and required to be in the range 90–140 GeV for both leading jets. The N-subjettiness [8] ratio $\tau_{21} = \tau_2/\tau_1$ has a value much smaller than unity for a jet with two subjets. For the signal selection, J1 and J2, both are required to have $\tau_{21} < 0.6$. The H-tagging of J1 and J2 further requires identifying their subjet pairs to be b-tagged with a probability of about 49% to contain at least one B-hadron, and the corresponding probability of about 1% of having no B/D-hadrons using DeepCSV [9] b-tagger. Events are classified into two categories: those having exactly three out of the four b-tagged subjets (3b category), and those which have all four subjets b-tagged (4b category).

For b), events are required to have at least two AK4 jets j1 and j2, which are separated from the H jets by $\Delta R > 1.2$, with $p_T > 50$ GeV and $|\eta| < 5$. To pass the VBF selections, these jets must lie in opposite η regions of the detector, and a pseudo-rapidity difference $|\Delta\eta(j1, j2)| > 5$. The invariant mass m_{jj} , reconstructed using these AK4 jets, is required to pass $m_{jj} > 300$ GeV.

The bulk graviton invariant mass m_{JJ} is reconstructed from the 4-momenta of the two Higgs jets, in events passing the above mentioned full selection criteria. The main multijet background is smoothly falling above which the signal is searched as a localised excess of events for a narrow resonance X. It is expected that the multijet background component in a true search at the HL-LHC will rely on the data for a precise result. From the analysis of current LHC data at $\sqrt{s} = 13$ TeV [2], it was found that the multijet backgrounds, measured in data, are a factor of 0.7 smaller than the estimated in simulation, hence the multijet background yield from simulation has been corrected by this factor, assuming this also holds for the simulations of the multijet processes at $\sqrt{s} = 14$ TeV. The m_{JJ} of the backgrounds thus obtained and are shown in Figure 2, while the event yields are given in Table 1 after full selection. The requirement of additional VBF jets does not result in any appreciable gain in the signal sensitivity because of strong dependency of VBF Jets on pileup. It is anticipated that the developments in the rejection of pileup jets in the high η region will eventually help to suppress the multijets background and improve the signal sensitivity further.

Figure 2: The m_{JJ} distributions for bulk gravitons (BG) of masses 1.5, 2, and 3 TeV, assuming a signal cross section of 1 fb. The distributions on the left are for the 3b and those on the right are for the 4b subjet b-tagged categories and for an average pileup of 200 [10].

Process	3b Category	3b Category	4b category	4b Category
	Events	Efficiency (%)	Events	Efficiency (%)
MultiJets	4755	1.6×10^{-3}	438	1.5×10^{-4}
BG($m_X=1.5$ TeV)	326	11	95.2	3.2
BG($m_X=2.0$ TeV)	316	11	81.2	2.7
BG($m_X=3.0$ TeV)	231	7.7	41.4	1.4

Table 1: Event yields and efficiencies for the signal and multijet background for an average pileup of 200. The product of the cross sections and branching fractions of the signals σ ($pp \rightarrow Xjj \rightarrow HHjj$) is assumed to be 1 fb [10].

Results:

The expected significance of the signal, assuming a production cross section of 1 fb is estimated considering all the systematic uncertainties. These uncertainties are based on the projected values for the full data set at the HL-LHC [11]. In addition, several measurement uncertainties are considered based on the 2016 search for a resonance decaying to a pair of boosted Higgs bosons [2], scaled by 0.5. The expected signal significance of a bulk graviton with the mass 2000 GeV, produced through vector boson fusion, with an assumed production cross section of 1 fb, is found to be 2.6σ for an integrated luminosity of 3 ab^{-1} . With higher mass of bulk graviton, there might be possible evidence of it with this analysis strategy at HL-LHC.

Figure 3: The expected signal significance for bulk graviton with explicit masses 1500, 2000, and 3000 GeV, assuming a production cross section of 1 fb. The data set corresponds to an integrated luminosity of 3 ab^{-1} and with a pileup of 200 [10].

References

- [1] Alexandra Carvalho. “Gravity particles from Warped Extra Dimensions, predictions for LHC”. In: (2014). arXiv: 1404.0102v4 [hep-ph].
- [2] CMS Collaboration. “Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ ”. In: *Phys. Lett. B* 781 (2018) 244 (2017). arXiv: 1710.04960v2 [hep-ex].
- [3] John Allison et al. “Geant4 developments and applications”. In: *IEEE Trans. Nucl. Sci.* 53 (2006), p. 270.
- [4] J. Alwall et al. “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”. In: *JHEP* 07 (2014), p. 079. arXiv: 1405.0301 [hep-ph].
- [5] Torbjörn Sjöstrand et al. “An Introduction to PYTHIA 8.2”. In: *Comput. Phys. Commun.* 191 (2015), p. 159. arXiv: 1410.3012 [hep-ph].
- [6] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. “The anti- k_t jet clustering algorithm”. In: *JHEP* 04 (2008), p. 063. arXiv: 0802.1189 [hep-ph].
- [7] Andrew J. Larkoski et al. “Soft drop”. In: *JHEP* 05 (2014), p. 146. arXiv: 1402.2657 [hep-ph].
- [8] Jesse Thaler and Ken Van Tilburg. “Identifying Boosted Objects with N-subjettiness”. In: *JHEP* 03 (2011), p. 015. arXiv: 1011.2268 [hep-ph].

- [9] A. M. Sirunyan et al. “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”. In: *Journal of Instrumentation* 13.5 (2018). arXiv: 1712.07158 [physics.ins-det].
- [10] CMS Collaboration. *Search for vector boson fusion production of a massive resonance decaying to a pair of Higgs bosons in the four b quark final state at the HL-LHC using the CMS Phase-2 detector*. Tech. rep. CMS-PAS-FTR-2018-003. CERN, 2018.
- [11] CMS Collaboration. *Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC*. Tech. rep. CMS-NOTE-2018-006. CERN, 2018.