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Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton–proton collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

A search for a massive resonance decaying into a pair of standard model Higgs bosons, in a final state consisting of two b quark–antiquark pairs, is performed. A data sample of proton–proton collisions at a centre-of-mass energy of 13 TeV is used, collected by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of 35.9 fb^{-1}. The Higgs bosons are highly Lorentz-boosted and are each reconstructed as a single large-area jet. The signal is characterized by a peak in the dijet invariant mass distribution, above a background from the standard model multijet production. The observations are consistent with the background expectations, and are interpreted as upper limits on the products of the *s*-channel production cross sections and branching fractions of narrow bulk gravitons and radions in warped extra-dimensional models. The limits range from 126 to 1.4 fb at 95% confidence level for resonances with masses between 750 and 3000 GeV, and are the most stringent to date, over the explored mass range.

1. Introduction

In the standard model (SM), the pair production of Higgs bosons (H) [1–3] in proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV is a rare process [4]. However, the existence of massive resonances decaying to Higgs boson pairs (HH) in many new physics models may enhance this rate to a level observable at the CERN LHC using the current data. For instance, models with warped extra dimensions (WED) [5] contain new particles such as the spin-0 radion [6–8] and the spin-2 first Kaluza–Klein (KK) excitation of the graviton [9–11], which have sizeable branching fractions to HH.

The WED models have an extra spatial dimension compactified between two branes, with the region between (called the bulk) warped via an exponential metric κl, κ being the warp factor and l the coordinate of the extra spatial dimension [12]. The reduced Planck scale ($\overline{M_{\rm Pl}} \equiv M_{\rm Pl}/8\pi$, $M_{\rm Pl}$ being the Planck scale) is considered a fundamental scale. The free parameters of the model are $\kappa/\overline{M_{\rm Pl}}$ and the ultraviolet cutoff of the theory $\Lambda_{\rm R} \equiv \sqrt{6}{\rm e}^{-\kappa l}\overline{M_{\rm Pl}}$ [6]. In pp collisions at the LHC, the graviton and the radion are produced primarily through gluon–gluon fusion and are predicted to decay to HH [13].

Other scenarios, such as the two-Higgs doublet models [14] (in particular, the minimal supersymmetric model [15]) and the Georgi–Machacek model [16] predict spin-0 resonances that are produced primarily through gluon–gluon fusion, and decay to an HH pair. These particles have the same Lorentz structure and effective couplings to the gluons and, for narrow widths, result in the same kinematic distributions as those for the bulk radion. Hence, the results of this paper are also applicable to this class of models.

Searches for a new particle X in the HH decay channel have been performed by the ATLAS [17–19] and CMS [20–24] Collaborations in pp collisions at $\sqrt{s} = 7$ and 8 TeV. More recently, the ATLAS Collaboration has published limits on the production of a KK bulk graviton, decaying to HH, in the $\rm b\overline{b}b\overline{b}$ final state, using pp collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 3.2 fb^{-1} [25]. Because the longitudinal components of the W and Z bosons couple to the Higgs field in the SM, a resonance decaying to HH potentially also decays into WW and ZZ, with a comparable branching fraction for $\rm X \to ZZ$, and with a branching fraction for $\rm X \to WW$ that is twice as large. Searches for $\rm X \to WW$ and ZZ have been performed by ATLAS and CMS [26–35].

This letter reports on the search for a massive resonance decaying to an HH pair, in the $\rm b\overline{b}b\overline{b}$ final state (with a branching fraction ≈33% [36]), performed using a data set corresponding to 35.9 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV. The search significantly improves upon the CMS analysis performed using the LHC data collected at $\sqrt{s} = 8$ TeV [24], and extends the searched mass range to 750–3000 GeV. This search is conducted for both the radion

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and the graviton, whereas the earlier search only considered the former.

In this search, the $X \to HH$ decay would result in highly Lorentz-boosted and collimated decay products of $H \to b\bar{b}$, which are referred to as H jets. These are reconstructed using jet substructure and jet flavour-tagging techniques [37–39]. The background consists mostly of SM multijet events, and is estimated using several control regions defined in the phase space of the masses and flavour-tagging discriminators of the two H jets, and the HH dijet invariant mass, allowing the background to be predicted over the entire range of m_X explored. The signal would appear as a peak in the HH dijet invariant mass spectrum above a smooth background distribution.

2. The CMS detector and event simulations

The CMS detector with its coordinate system and the relevant kinematic variables is described in Ref. [40]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The tracker covers a pseudorapidity η range from -2.5 to 2.5 with the ECAL and the HCAL extending up to $|\eta| = 3$. Forward calorimeters in the region up to $|\eta| = 5$ provide almost hermetic detector coverage. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, covering a region of $|\eta| < 2.4$.

Events of interest are selected using a two-tiered trigger system [41]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. Events are selected at the trigger level by the presence of jets of particles in the detector. The L1 trigger algorithms reconstruct jets from energy deposits in the calorimeters. At the HLT, physics objects (charged and neutral hadrons, electrons, muons, and photons) are reconstructed using a particle-flow (PF) algorithm [42]. The anti-k_T algorithm [43,44] is used to cluster these objects with a distance parameter of 0.8 (AK8 jets) or 0.4 (AK4 jets).

Bulk graviton and radion signal events are simulated at leading order using the MadGraph5_amc@nlo 2.3.3 [45] event generator for masses in the range 750–3000 GeV and widths of 1 MeV (narrow width approximation). The NNPDF3.0 leading order parton distribution functions (PDFs) [46], taken from the LHAPDF6 PDF set [47–50], with the four-flavour scheme, is used. The showering and hadronization of partons is simulated with pythia 8.212 [51]. The herwig++ 2.7.1 [52] generator is used for an alternative model to evaluate the systematic uncertainty associated with the parton shower and hadronization. The tune CUETP8M1-NNPDF2.3LO [53] is used for pythia 8, while the EE5C tune [54] is used for herwig++.

The background is modelled entirely from data. However, simulated background samples are used to develop and validate the background estimation techniques, prior to being applied to the data. These are multijet events, generated at leading order using MadGraph5_amc@nlo, and $t\bar{t}$ + jets, generated at next-to-leading order using powheg 2.0 [55–57]. Both these backgrounds are interfaced to pythia 8 for simulating the parton shower and hadronization. Studies using simulations established that the multijet component is more than 99% of the background, with the rest mostly from $t\bar{t}$ + jets production.

All generated samples were processed through a Geant4-based [58,59] simulation of the CMS detector. Multiple pp collisions may occur in the same or adjacent LHC bunch crossings (pileup) and contribute to the overall event activity in the detector. This effect is included in the simulations, and the samples are reweighted to match the number of pp interactions observed in the data, assuming a total inelastic pp collision cross section of 69.2 mb [60].

3. Event selection

Events were collected using several HLT algorithms. The first required the scalar p_T sum of all AK4 jets in the event (H_T) to be greater than 800 or 900 GeV, depending on the LHC beam instantaneous luminosity. A second trigger criterion required $H_T \geq 650$ GeV, with a pair of AK4 jets with invariant mass above 900 GeV and a pseudorapidity separation $|\Delta\eta| < 1.5$. A third set of triggers selected events with the scalar p_T sum of all AK8 jets greater than 650 or 700 GeV and the presence of an AK8 jet with a "trimmed mass" above 50 GeV, i.e. the jet mass after removing remnants of soft radiation using jet trimming technique [61]. The fourth triggering condition was based on the presence of an AK8 jet with $p_T > 360$ GeV and trimmed mass greater than 30 GeV. The last trigger selection accepted events containing two AK8 jets having $p_T > 280$ and 200 GeV with at least one having trimmed mass greater than 30 GeV, together with an AK4 jet passing a loose b-tagging criterion.

The pp interaction vertex with the highest $\sum p_T^2$ of the associated clusters of physics objects is considered to be the one associated with the hard scattering interaction, the primary vertex. The physics objects are the jets, clustered using the jet finding algorithm [43,44] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets. The other interaction vertices are designated as pileup vertices.

To mitigate the effect of pileup, particles are assigned weights using the pileup per particle identification (PUPPI) algorithm [62], with the weight corresponding to its estimated probability to originate from a pileup interaction. Charged particles from pileup vertices receive a weight of zero while those from the primary vertex receive a weight of one. Neutral particles are assigned a weight between zero and one, with higher values for those likely to originate from the primary vertex. Particles are then clustered into AK8 jets. The vector sum of the weighted momenta of all particles clustered in the jet is taken to be the jet momentum. To account for detector response nonlinearity, jet energy corrections are applied as a function of jet η and p_T [63,64]. In each event, the leading and the subleading p_T AK8 jets, j_1 and j_2, respectively, are required to have $p_T > 300$ GeV and $|\eta| < 2.4$.

The removal of events containing isolated leptons (electrons or muons) with $p_T > 20$ GeV and $|\eta| < 2.4$ helps suppress $t\bar{t}$ + jets and diboson backgrounds. The isolation variable is defined as the scalar p_T sum of the charged and neutral hadrons, and photons in a cone of $\Delta R = 0.3$ for an electron or $\Delta R = 0.4$ for a muon, where $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, ϕ being the azimuthal angle in radians. The energy from pileup deposited in the isolation cone, and the p_T of the lepton itself, is subtracted [65,66]. The isolation requirement removes jets misidentified as leptons. Additional quality criteria are applied to improve the purity of the isolated lepton samples. Electrons passing combined isolation and quality criteria corresponding to a selection efficiency of 90% (70%) are designated "loose" ("medium") electrons. For the "loose" ("medium") muons, the total associated efficiency is 100% (95%). The probability of a jet to be misidentified as an electron or a muon is in the range