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Search for resonant pair production of Higgs bosons decaying to two bottom quark–antiquark pairs in proton–proton collisions at 8 TeV

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ABSTRACT

A model-independent search for a narrow resonance produced in proton–proton collisions at $\sqrt{s} = 8$ TeV and decaying to a pair of 125 GeV Higgs bosons that in turn each decays into a bottom quark–antiquark pair is performed by the CMS experiment at the LHC. The analyzed data correspond to an integrated luminosity of 17.9 fb^{-1}. No evidence for a signal is observed. Upper limits at a 95% confidence level on the production cross section for such a resonance, in the mass range from 270 to 1100 GeV, are reported. Using these results, a radion with decay constant of 1 TeV and mass from 300 to 1100 GeV, and a Kaluza–Klein graviton with mass from 380 to 830 GeV are excluded at a 95% confidence level.

1. Introduction

Following the discovery of a Higgs boson (H) at the CERN LHC [1–3], with mass around 125 GeV and properties so far consistent with the standard model (SM) of particle physics, it has become important to search for new resonances that decay into pairs of such Higgs bosons. While non-resonant pair production of the Higgs boson is allowed in the SM, the theoretical production cross section is approximately 10 fb [4] and well beyond the sensitivity of currently acquired data. However, several well-motivated hypotheses of physics beyond the standard model posit narrow-width resonances that decay into pairs of Higgs bosons, and could be produced with large enough cross sections to be probed with existing data. The radion [5] and Kaluza–Klein (KK) gravitons in the Randall–Sundrum (RS1) [6] model of warped extra dimensions are examples of such resonances [7].

This letter reports the results of a model-independent search for the resonant pair production of Higgs bosons. The search for the narrow width resonance, denoted by X, is performed in the 270–1100 GeV mass range. Data from proton–proton collisions at the LHC and recorded by the CMS experiment corresponding to an integrated luminosity of 17.9 ± 0.5 fb^{-1} at $\sqrt{s} = 8$ TeV is used. We perform this search for the case where both Higgs bosons decay into bottom quark–antiquark pairs ($b\bar{b}$) [8]. The main challenge of this search is to distinguish the signal of four bottom quarks in the final state that hadronize into jets (b jets) from the copious multijet background described by quantum chromodynamics (QCD) in pp collisions. We address this challenge by suitable event selection criteria that include dedicated b-jet identification techniques and a model of the multijet background that is validated in data control regions. Our results may be compared with a search performed by the ATLAS experiment [9] that also probes the physics of resonant Higgs boson pair production, albeit in the channel where one Higgs boson decays to bottom quarks and the other decays to photons.

2. Detector and event reconstruction

A detailed description of the CMS detector, together with a description of the coordinate system used and the relevant kinematic variables, can be found in Ref. [10]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter that generates an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are detected and their properties measured in

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gas-ionization detectors embedded in a steel flux-return yoke outside the solenoid. Jets are reconstructed using the anti-k_T clustering algorithm [11,12] with a distance parameter of 0.5 applied on the collection of particle candidates reconstructed by the particle-flow (PF) algorithm [13,14]. The PF algorithm reconstructs and identifies each individual particle with a combination of information from the various elements of the CMS detector. To mitigate the effect of additional particles that do not originate from the hard interaction in jet reconstruction, we subtract charged hadrons that do not arise from the primary vertex associated with the jet from the collection of clustered particles. Further, an average neutral energy density from particles not arising from the primary vertex is evaluated and subtracted from the jets [15]. Energy corrections for the jets are determined as functions of the jet transverse momentum p_T and pseudorapidity $|\eta|$. Jet identification criteria [16] to reject detector noise misidentified as jets, and jets not originating from the hard interaction are also applied.

In order to identify (tag) b jets, we rely on the fact that bottom quarks hadronize into b hadrons which have decay lengths of the order of $c\tau = 450$ μm. Thus, their decay products originate from secondary vertices made of tracks that have impact parameters with respect to the primary vertex of a similar scale. The pixel tracker provides an impact parameter resolution of about 15 μm for charged tracks with $|\eta| < 2.4$. To maximize the b-tagging performance of the detector, we combine the output discriminants of several b-tagging algorithms described in Ref. [17] with a trained artificial neural network. This we call the combined multivariate (CMVA) algorithm. In particular, we combine the outputs of the combined secondary vertex (CSV) tagger that uses secondary vertices identified by the inclusive vertex finder (IVF) algorithm [18], the jet probability (JP) tagger, and the two soft lepton taggers.

The first level of the trigger, consisting of customized processors, collects data for this analysis using information from the calorimeters and requires two jets to exceed p_T thresholds of 56 or 64 GeV, depending on luminosity conditions. The second level of the trigger, consisting of software algorithms executed on a farm of commercial processors, uses information from the entire detector to reconstruct PF jets, and requires four PF jets with $|\eta| < 2.4$ and $p_T > 30$ GeV, of which two jets must have $p_T > 80$ GeV. Further, to record signal events and reject background QCD multijet events, two jets are required to be tagged by the CSV b-tagging algorithm implemented at the trigger.

3. Simulated samples

To model the production of a generic narrow-width spin-0 resonance, we use a Monte Carlo simulation of the RS1 radion produced through gluon fusion. The angular distributions of a spin-2 resonance are distinct from those of a spin-0 resonance, and result in different kinematic distributions. Therefore, we evaluate the signal efficiencies for a narrow-width spin-2 resonance from a separate simulation of the first excitation of the KK graviton produced through gluon fusion in the same extra dimension scenario as the radion. The resonance is forced to decay to a pair of Higgs bosons where both Higgs bosons decay to $b\bar{b}$. Samples of these signal events, as well as background events from diboson, W + jets, Z + jets and top-quark pair production ($t\bar{t}$) processes, are generated using the MadGraph 5.1 [19] program interfaced with pythia 6.4 [20] for parton showering and hadronization. QCD multijet event samples are simulated with the pythia 6.4 program. A sample of events where the Higgs boson is produced in association with a Z boson is simulated using the powheg event generator [21–23] interfaced with the herwig++ [24] program for showering and hadronization. We set the pythia 6.4 parameters for the underlying event to the Z2* tune [25]. The response of the CMS detector is modeled using Geant4 [26].

On average, 21 pp interactions occurred per bunch crossing in the data used in this analysis. Additional simulated pp interactions overlapping with the event of interest were added to the simulated samples to reproduce the distribution of the number of primary vertices per event reconstructed in data.

4. Event selection

The trigger-level jet p_T thresholds confine our search for a narrow-width $X \to HH \to b\bar{b}b\bar{b}$ resonance to masses above 270 GeV. Beyond $m_X \approx 800$ GeV, the selection efficiency is increasingly limited by the merging of jets from the same Higgs boson, and we curtail this search at 1100 GeV. The kinematic distributions of the decay products vary substantially over this mass range. Therefore, to optimize the search sensitivity, we use different event selection criteria in three main kinematic regions: the low-mass region (LMR) for mass hypotheses from 270 to 450 GeV, the medium-mass region (MMR) for masses from 450 to 730 GeV, and the high-mass region (HMR) for masses from 730 to 1100 GeV.

Event selection begins with the identification of events containing at least four jets in the central region of the detector ($|\eta| < 2.4$) that are b-tagged and have $p_T > 40$ GeV. To b-tag a jet, we require it to pass a working point for the CMVA algorithm that maximizes the sensitivity of this search. For jets with $p_T > 40$ GeV and $|\eta| < 2.4$ this working point yields a 75% efficiency for tagging jets originating from b hadrons and a mistagging rate of 3% for light-flavor jets. For the LMR, we combine these b jets into pairs to create HH candidates such that $|m_H - 125 \text{ GeV}| < 35$ GeV for each candidate Higgs boson. The mass resolution on the Higgs boson in the LMR is found to be approximately 9 GeV. Selected HH candidates are required to have at least two jets with $p_T > 90$ GeV. In the MMR, signal events have large Lorentz factors for the Higgs boson candidates. Therefore, HH candidates for this region are constructed from four jets such that the $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ between the jets associated with an H candidate remain within 1.5, where $\Delta\eta$ and $\Delta\phi$ are the differences in the pseudorapidities and azimuthal angles of the two jets. For the HMR, we use the same criteria used in the MMR with an additional requirement of $p_T > 300$ GeV on one of the H candidates to better discriminate signal events from background. In all three regions, in case of multiple HH candidates in an event, the combination with the smallest $|m_{H_1} - m_{H_2}|$ is chosen. Having identified the two Higgs boson candidates in each event, we plot their masses, m_{H_1} and m_{H_2}, on a two-dimensional histogram as shown in Fig. 1. H_1 and H_2 are chosen at random from the two reconstructed H candidates. As the final selection criterion applied in each of the three mass hypothesis regions, we require events to fall within the signal region (SR) defined as $\sqrt{\Delta m^2_{H_1} + \Delta m^2_{H_2}} < 17.5$ GeV, where $\Delta m_{H_{1,2}} = m_{H_{1,2}} - 125$ GeV.

The efficiencies of these selection criteria for spin-0 and spin-2 resonances at representative masses are shown in Table 1. The major loss in efficiency for all mass hypotheses comes from the b-tagging requirement for 4 jets. For the 300 GeV mass hypothesis, this is compounded by the trigger inefficiency. The distribution of the aforementioned ΔR between jets from a single Higgs boson is narrower for the spin-2 resonance, and thus requiring $\Delta R < 1.5$ results in a higher efficiency for it.

5. Signal modeling

For signal events, the aforementioned event selection criteria are expected to produce a sharp peak in the m_X distribution over a relatively featureless background from events arising from SM