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Search for heavy resonances decaying into a vector boson and a Higgs boson in final states with charged leptons, neutrinos, and b quarks

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A search for heavy resonances decaying to a Higgs boson and a vector boson is presented. The analysis is performed using data samples collected in 2015 by the CMS experiment at the LHC in proton–proton collisions at a center-of-mass energy of 13 TeV, corresponding to integrated luminosities of 2.2–2.5 fb^{-1}. The search is performed in channels in which the vector boson decays into leptonic final states ($\mathrm{Z} \to \nu\nu$, $\mathrm{W} \to \ell\nu$, and $\mathrm{Z} \to \ell\ell$, with $\ell = \mathrm{e}, \mu$), while the Higgs boson decays to collimated b quark pairs detected as a single massive jet. The discriminating power of a jet mass requirement and a b jet tagging algorithm are exploited to suppress the standard model backgrounds. The event yields observed in data are consistent with the background expectation. In the context of a theoretical model with a heavy vector triplet, a resonance with mass less than 2 TeV is excluded at 95% confidence level. The results are also interpreted in terms of limits on the parameters of the model, improving on the reach of previous searches.

1. Introduction

The discovery of a Higgs boson H at the CERN LHC [1–3] suggests that the standard model (SM) mechanism that connects electroweak (EW) symmetry breaking to the generation of particle masses is largely correct. However, the relatively light value of the Higgs boson mass $m_{\mathrm{H}} = 125.09 \pm 0.21\,(\mathrm{stat}) \pm 0.11\,(\mathrm{syst})\,\mathrm{GeV}$ [4–7] leaves the hierarchy problem unsolved [8], pointing to phenomena beyond the SM, which could be unveiled by searches at the LHC. Many theories that incorporate phenomena beyond the SM postulate the existence of new heavy resonances coupled to the SM bosons. Among them, weakly coupled spin-1 Z' [9,10] and W' models [11] or strongly coupled Composite Higgs [12–14], and Little Higgs models [15–17] have been widely discussed.

A large number of models are generalized in the heavy vector triplet (HVT) framework [18], which introduces one neutral (Z') and two electrically charged (W') heavy resonances. The HVT model is parametrized in terms of three parameters: the strength g_{V} of a new interaction; the coupling c_{H} between the heavy vector bosons, the Higgs boson, and longitudinally polarized SM vector bosons; and the coupling c_{F} between the HVT bosons and the SM fermions. In the HVT scenario, model B with parameters $g_{\mathrm{V}} = 3$, $c_{\mathrm{H}} = 0.976$, and $c_{\mathrm{F}} = 1.024$ [18] is used as the benchmark. With these values, the couplings of the heavy resonances to fermions and to SM bosons are similar, yielding a sizable branching fraction for the heavy resonance decay into a SM vector boson W or Z (generically labeled as V) and a Higgs boson [18].

Bounds from previous searches [19–22] require the masses of these resonances to be above 1 TeV in the HVT framework. In this mass region, the two bosons produced in the resonance decay would have large Lorentz boosts in the laboratory frame. When decaying, each boson would generate a pair of collimated particles, a distinctive signature, which can be well identified in the CMS experiment. Because of the large predicted branching fraction, the decay of high-momentum Higgs bosons to $\mathrm{b\bar{b}}$ final states is considered. The Higgs boson is reconstructed as one unresolved jet, tagged as containing at least one bottom quark. Backgrounds from single quark and gluon jets are reduced by a jet mass requirement. In order to discriminate against the large multijet background, the search is focused on the leptonic decays of the vector bosons ($\mathrm{Z} \to \nu\nu$, $\mathrm{W} \to \ell\nu$, and $\mathrm{Z} \to \ell\ell$, with $\ell = \mathrm{e}, \mu$).

The main SM background process is the production of vector bosons with additional hadronic jets (V+jets). The estimation of this background is based on events in signal-depleted jet mass sidebands, with a transfer function, derived from simulation, from the sidebands to the signal-enriched region. Top quark production also accounts for a sizable contribution to the background in 1ℓ final states, and is determined from simulation normalized to data in dedicated control regions. Diboson production processes, includ-

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ing pairs of vector bosons (VV) and the SM production of a Higgs boson and vector boson (VH), represent minor contributions to the overall background and are estimated from simulation. A signal would produce a localized excess above a smoothly falling background in the distribution of the kinematic variable m_{VH}, whose definition and relationship to the resonance mass m_{X} depends on the final state. Results are interpreted in the context of HVT models in the benchmark scenario B [18].

2. Data and simulated samples

The data samples analyzed in this study were collected with the CMS detector in proton–proton collisions at a center-of-mass energy of 13 TeV during 2015. The samples correspond to integrated luminosities of 2.2–2.5 fb^{-1}, depending on the final state considered.

Simulated signal events are generated at leading order (LO) according to the HVT model B [18] with the MadGraph5_amc@nlo v5.2.2.2 matrix element_generator [23]. The Higgs boson is required to decay into a $\mathrm{b\bar{b}}$ pair, and the vector boson into leptons. A contribution from vector boson decays into τ leptons is also included through subsequent decays to e or μ that satisfy the event selection. Different m_{X} hypotheses in the range 800 to 4000 GeV are considered, assuming a resonance width narrow enough (0.1% of the resonance mass) to be negligible with respect to the experimental resolution. This approximation is valid in a large fraction of the HVT parameter space, and will be discussed in Section 8.

The analysis utilizes a set of simulated samples to characterize the main SM background processes. Samples of V+jets events are produced with MadGraph5_amc@nlo and normalized to the next-to-next-to-leading-order (NNLO) cross section, computed using fewz v3.1 [24]. The V boson p_{T} spectra are corrected to account for next-to-leading-order (NLO) QCD and EW contributions [25]. Top quark pair production is simulated with the NLO powheg v2 generator [26–28] and rescaled to the cross section value computed with Top++ v2.0 [29] at NNLO. Minor SM backgrounds, such as VV and VH production, and single top quark (t+X) production in s-channel, t-channel, and in tW associated production, are simulated at NLO with MadGraph5_amc@nlo. Multijet production is simulated at leading order with the same generator.

Parton showering and hadronization processes are simulated by interfacing the event generators to pythia 8.205 [30,31] with the CUETP8M1 [32,33] tune. The NNPDF 3.0 [34] parton distribution functions (PDFs) are used to model the momentum distribution of the colliding partons inside the protons. Generated events, including additional proton–proton interactions within the same bunch crossing (pileup) at the level observed during 2015 data taking, are processed through a full detector simulation based on Geant4 [35] and reconstructed with the same algorithms used for data.

3. CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity [36] coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the solenoid. For nonisolated particles of transverse momentum $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [37]. The ECAL provides coverage up to $|\eta| < 3.0$. The dielectron mass resolution for $\mathrm{Z} \to \mathrm{ee}$ decays when both electrons are in the ECAL barrel is 1.9%, and is 2.9% when both electrons are in the endcaps. The HCAL covers the range of $|\eta| < 3.0$, which is extended to $|\eta| < 5.2$ through forward calorimetry. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Combining muon tracks with matching tracks measured in the silicon tracker results in a p_{T} resolution of 2–10% for muons with $0.1 < p_{\mathrm{T}} < 1\,\mathrm{TeV}$ [38].

The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to about 1 kHz, before data storage.

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [36].

4. Event reconstruction

In CMS, a global event reconstruction is performed using a particle-flow (PF) algorithm [39,40], which uses an optimized combination of information from the various elements of the CMS detector to reconstruct and identify individual particles produced in each collision. The algorithm identifies each reconstructed particle either as an electron, a muon, a photon, a charged hadron, or a neutral hadron.

The PF candidates are clustered into jets using the anti-k_{T} algorithm [41] with a distance parameter $R = 0.4$ (AK4 jets) or $R = 0.8$ (AK8 jets). In order to suppress the contamination from pileup, charged particles not originating from the primary vertex, taken to be the one with the highest sum of p_{T}^2 over its constituent tracks, are discarded. The residual contamination removed is proportional to the event energy density and the jet area estimated using the FastJet package [42,43]. Jet energy corrections, extracted from simulation and data in multijet, γ+jets, and Z+jets events, are applied as functions of the transverse momentum and pseudorapidity to correct the jet response and to account for residual differences between data and simulation. The jet energy resolution amounts typically to 5% at 1 TeV [44]. Jets are required to pass an identification criterion, based on the jet composition in terms of the different classes of PF candidates, in order to remove spurious jets arising from detector noise. The pruning algorithm [45], which is designed to remove contributions from soft radiation and additional interactions, is applied to AK8 jets. The pruned jet mass m_{j} is defined as the invariant mass associated with the four-momentum of the pruned jet, after the application of the jet energy corrections [44]. The AK8 jets are split into two subjets using the soft drop algorithm [46,47].

The combined secondary vertex algorithm [48] is used for the identification of jets that originate from b quarks (b tagging). The algorithm uses the tracks and secondary vertices associated with AK4 jets or AK8 subjets as inputs to a neural network to produce a discriminator with values between 0 and 1, with higher values indicating a higher b quark jet probability. The loose and the tight operating points are about 85 and 50% efficient, respectively, for b jets with p_{T} of about 100 GeV, with a false-positive rate for light-flavor jets of about 10 and 0.1%.