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Search for new resonances decaying into W, Z and H bosons at CMS

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Beyond the standard model theories like Extra-Dimensions and Composite Higgs scenarios predict the existence of very heavy resonances compatible with a spin 0 (Radion), spin 1 (W', Z') and spin 2 (Graviton) particle with large branching fractions in pairs of standard model bosons and negligible branching fractions to light fermions. We present an overview of searches for new physics containing W, Z or H bosons in the final state, using proton-proton collision data collected with the CMS detector at the CERN LHC. Many results use novel analysis techniques to identify and reconstruct highly boosted final states that are created in these topologies. These techniques provide increased sensitivity to new high-mass particles over traditional search methods.

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1. Introduction

The discovery of a Higgs boson H at the CERN LHC [1, 2] demonstrates the validity of the standard model (SM) mechanism that connects electroweak (EW) symmetry breaking to the generation of particle masses. However, the relatively small value of the 125 GeV Higgs boson mass [3] leaves many questions unexplained, pointing to phenomena beyond the SM. Several credited theories postulate the presence of heavy resonances (X) coupled to the SM bosons: among them, weakly coupled spin-1 Z' [4] and W' models [5] or strongly coupled Composite Higgs [6], and Little Higgs models [7]. A large number of these models are generalized in the heavy vector triplet (HVT) framework [8], which introduces one neutral (Z') and two electrically charged (W') heavy resonances. An alternative explanation of the extreme fine-tuning of the Higgs boson mass can be provided by the presence of a bulk graviton described by the RS model in warped extra dimensions [9], or the so-called tower of Kaluza-Klein (KK) excitations of a spin-2 graviton [10]. These resonances are expected to have a mass from few hundreds GeV up to few TeV, and thus they can be accessible to LHC. Several searches are performed by the CMS experiment [11] based on 2.3 fb^{-1} and 35.9 fb^{-1} collected during the 2015 and 2016 data taking periods.

2. $X \to VV \to q\bar{q}q\bar{q}$

One of the most sensitive final states for heavy diboson resonance searches is represented by hadronic decays of the two vector bosons (V = W, Z) [12]. The dominant multijet production at LHC is compensated by the large branching fraction of the decay into quarks. This search is performed on the entire 2016 data set, accounting for 35.9 fb^{-1} of data. Due to the large mass of the resonance, the pair of bosons have a large Lorentz boost and the quarks produced in their decay are collimated, and reconstructed within a single hadronic jet with radius parameter 0.8. The investigation of the jet substructure allows an efficient identification of the 2-prong jets typically originating from massive particle decays, significantly reducing the dominant 1-pronged jets from multijet background. The two most indicative variables to perform the V-boson tagging are the jet mass, and the N-subjettiness variable, as shown in Fig. 1. Both are built upon a novel pile-up mitigation algorithm, denoted as pileup-per-particle identification (PUPPI) [13]. The soft-drop algorithm [14, 15], which is designed to remove contributions from soft radiation and additional interactions, is applied to PUPPI jets to calculate the jet mass. Dedicated corrections are applied to the jet mass to match the scale and resolution as measured in data from a sample enriched in merged $W \to q\bar{q}$ decays from top quarks [16].

Events are divided in categories according to the jet mass (W or Z mass region) and the purity (high or low purity) or the two vector boson candidates. An additional category, targeting excited quark resonances $q^* \to qV$, selects events when only one jet is compatible with the vector boson hypothesis. The background is estimated separately in the different categories by fitting a power law function with a variable number of parameters, depending on the result of a Fisher F-test in each category (Fig. 2), and then combined to set stringent limits on the cross section and branching ratio of the new resonance. Heavy Z' and W' resonances are excluded up to 2.7 and 3.6 TeV, as reported in Fig. 3, in a benchmark scenario where the couplings to fermions are suppressed with respect to the couplings to bosons, resulting in a branching fraction to SM bosons close to unity

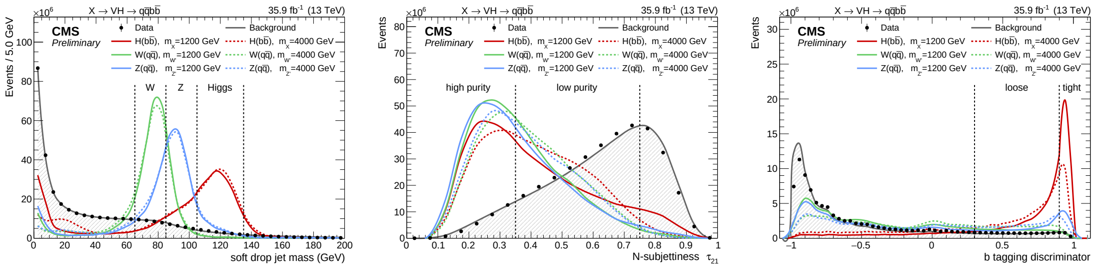

Figure 1: Distribution of the soft-drop PUPPI mass (left), N-subjettiness τ_{21} (right), and boosted $H \to b\bar{b}$ tagger discriminator (bottom) for data, simulated background, and signal. The dashed vertical lines represent the boundary values of the categories [17].

(HVT model B). A bulk graviton is not excluded in the $\tilde{k} = 0.5$ scenario, but stringent limits are set on its cross section. Excited quarks decaying into qZ and qW with masses below 4.7 and 5.0 TeV are excluded as well.

3. $X \to VH \to q\bar{q}b\bar{b}$

Another sensitive channel is represented by the decay of the heavy resonance into a vector boson and a Higgs boson, where the vector boson decays hadronically and the Higgs boson decays primarily into a pair of b quarks [17]. This analysis shares many reconstruction and background estimation techniques with the VV search, and both of them are performed on 35.9 fb^{-1} collected in 2016. On the other hand, a different jet mass window is used to identify Higgs boson candidates, and a dedicated b tagging algorithm [18] has been developed specifically to identify the simultaneous presence of two b quarks from boosted $H \to b\bar{b}$ decays and discriminate against the gluon and light quark-initiated jets copiously produced in multijet events (Fig. 1). Similarly to the τ_{21} variable in the vector boson candidate, two categories are defined according to the b tagging discriminator score, loose and tight b tagging. The signal presence is tested in data from the combination of the eight search categories. A heavy Z' and W' singlet can be excluded up to 2.4 and 3.3 TeV, respectively. These exclusion limits are used to put stringent limits on the model parameters, excluding a mass-degenerate vector triplet up to 3.4 TeV in HVT model B.

4. $X \to ZV \to \ell\ell q\bar{q}$

Leptonic final states represent an attractive alternative to hadronic channels, thanks to the large selection efficiency and the natural discrimination offered by high momentum, isolated leptons. The CMS experiment presents a search for resonances decaying into a Z boson and a vector boson, where the Z boson decays into a pair of electrons or muons, and the vector boson into a pair of quarks [19]. Dedicated reconstruction techniques have been employed to avoid losses of efficiency in the lepton reconstruction and identification in case of a small angular separation between them. Two categories with different purities are defined, and events are split according to the lepton flavor. The background distribution is estimated with an hybrid method, based on data events in the jet mass sidebands, and interpolated to the signal region (Fig. 1) through a transfer function derived from simulated events. The search has been performed with a fraction of the 2016 data set counting

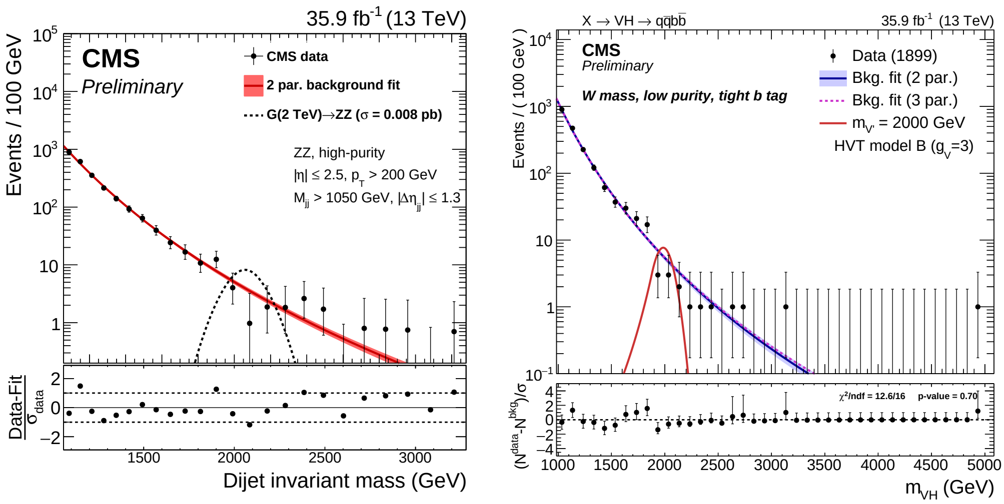

Figure 2: Observed data (black markers) and estimated background (red solid line) in the ZZ high purity category of the hadronic VV analysis (left) [12], and in the low purity, tight b tagging category of the hadronic VH analysis (right) [17].

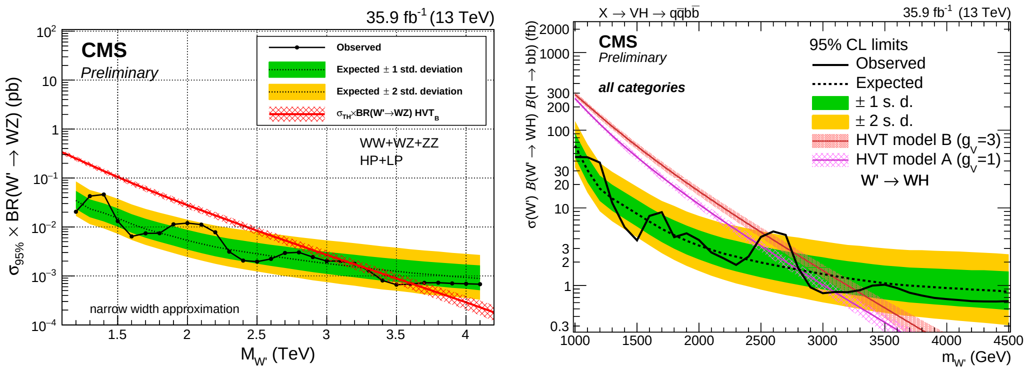

Figure 3: 95% CL exclusion limits on the cross section and branching ratio of heavy W' resonance in the hadronic VV (left) [12] and hadronic VH (right) [17] analyses. The cross section predicted by the HVT model B is represented by the red line.

12.9 fb^{-1}, and interpreted in the context of heavy W' models, excluding a W' with mass smaller than 2.3 TeV in HVT model B and 2.0 TeV in HVT model A (Fig. 4), the latter being a scenario where the new resonances decay primarily into fermions [8].

5. $X \to WV \to \ell\nu q\bar{q}$

The search for heavy resonances decaying into a W boson and a vector boson [20] follows a similar strategy of the ZV analysis. The W boson is reconstructed from the lepton decay, and the momentum of the neutrino is recovered from the missing energy measured in the detector and by imposing the kinematical constraint of the W boson mass. In addition to the usual high and low purity categories, events are split in two further categories according to the jet mass of the hadronic $V \to q\bar{q}$ decay, separating a $W \to q\bar{q}$ and a $Z \to q\bar{q}$ enriched regions. The mass range is extended down to 600 GeV by relaxing the kinematic selections. The background prediction method is similar to the one described for the VZ search. In HVT model A, a W' resonance with mass smaller than 2.0 TeV is excluded at 95% CL (Fig. 4).

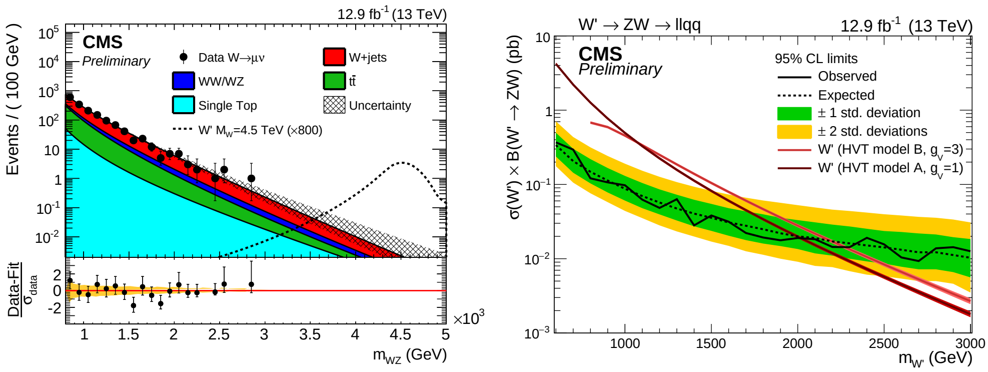

Figure 4: Reconstructed WZ candidate mass in the single muon channel (left) [20], and exclusion limits on the cross section and branching ratio of a W' resonance in the context of the $X \to ZV \to \ell\ell q\bar{q}$ search (right) [19]. The HVT model A and model B are represented by the orange and red lines.

6. $X \to VH \to (\nu\nu, \ell\nu, \ell\ell)b\bar{b}$

Searches for VH resonances have been performed in leptonic final states as well [21]. Several final states are probed to consider all possible leptonic decay modes of the vector boson: a large amount of missing energy and the absence of isolated leptons is an indication of a $Z \to \nu\nu$ decay; a single, isolated lepton and a moderate amount of missing energy can be interpreted as a $W \to \ell\nu$ decay; and two opposite sign, same flavor leptons whose invariant mass is compatible with m_Z are suitable as Z boson candidates. The Higgs boson is identified though its decay into pair of b-quarks, clustered in the same large-cone jet, with a mass compatible to m_H. The b tagging identification relies on the splitting of the original jets into two subjets, with either one or both can be independently b tagged. The main background is estimated from the jet mass sidebands using a transfer function from simulation, and the significant contribution of the top quark pair production is derived from appropriate control regions (Fig. 5). The analysis, performed on 2.1–2.5 fb^{-1} collected during 2015, excludes heavy mass-degenerate triplets up to 2.0 TeV in HVT model B, and sets stringent limits on the HVT parameters.

7. $X \to HH \to b\bar{b}b\bar{b}$

The search for Higgs boson resonances [22], with the Higgs bosons both decaying into pair of b quarks, is motivated by the potentially large branching fraction of spin-0 radions and spin-2 gravitons, depending on the parameters of the models. The CMS analysis is performed on the 2015 data set, and consists of two independent background estimation methods. In the first one, Higgs boson identification relies on subjet b tagging, and the background is estimated through a direct fit with exponential functions to the resonance mass distribution, as shown in Fig. 5. The background distribution in second method is estimated from a signal-depleted region with a b tag veto, and the

Higgs boson identification is performed by the algorithm used in the hadronic VH search. Limits are set on the production cross section and on the new physics models, excluding a radion with $\Lambda_R = 1$ TeV with mass below 1.7 TeV.

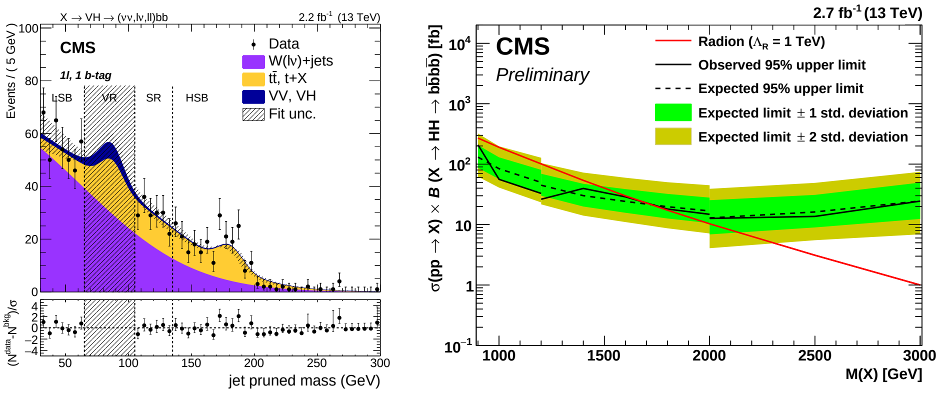

Figure 5: Jet mass distribution for the different backgrounds in the single lepton, 1 subjet b tag category of the VH leptonic analysis (left) [21]. The exclusion limits of the hadronic HH search compared to the radion cross section (right) [22]; the two background estimation methods are used in different mass ranges: the fit method is used in the central part of the spectrum, and the other in the low and high mass regions.

8. Combination of diboson searches

The searches for heavy resonances decaying into vector bosons based on 19.7 fb^{-1} of $\sqrt{s} = 8$ TeV data collected in 2012 and 2.2–2.6 fb^{-1} of $\sqrt{s} = 13$ TeV data set have been combined to increase the sensitivity to new physics models [23]. The combination has been made possible thanks to the natural orthogonality among the individual searches (Fig. 1), and the common reconstruction techniques. The combination possess a significant advantage over the single search, and new heavy triplet resonances are excluded up to 2.4 TeV in model B. The considered data set does not allow to directly exclude a bulk graviton in the $\tilde{k} = 0.5$ scenario, excluding up to three times the predicted cross section. Although the searches performed on the data collected in 2016 already retain a better sensitivity, this combination represented the most stringent result at the time.

9. Summary and future outlook

The LHC Run II has provided a significant amount of data at an unprecedented center of mass energy of 13 TeV, laying the foundations for a new generation of searches for diboson resonances in a variety of final states. New reconstruction techniques for boosted objects and pile-up mitigation algorithm have been commissioned during 2016, ensuring equivalent and in several cases better reconstruction efficiency and stability in spite of the harsher data taking conditions. Although no significant excess above the SM expectation has been observed, the corresponding limits push the possible masses of heavy vectors, gravitons and similar resonances above the 3 TeV range, far beyond previous results from Run I and analyses based on 2015 data. The LHC 2017 and 2018 data taking periods promise even more stringent limits, or possibly a discovery, thanks to the significant increase of the integrated luminosity.

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