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Searches for heavy resonances decaying into W, Z, and Higgs bosons with the CMS detector

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A summary of searches for heavy resonances decaying to a pair of bosons is presented, using pp collision data at $\sqrt{s} = 13$ TeV collected by the CMS detector at the LHC during 2016. A striking feature common to most of these analyses is their boosted topology, in which the decay products of the considered bosons (both electroweak W and Z bosons and the Higgs boson) are expected to be highly energetic and close in angle, requiring a non-trivial identification of the final-state particles. The exploitation of jet substructure techniques allows an increase of the sensitivity of the searches where at least one boson decays hadronically. Various background estimation techniques are utilized, either based on hybrid data-simulation approaches or only relying on control regions in data. The data are found to be consistent with the background expectations, and the results are interpreted in the context of the bulk graviton and heavy vector triplet models.

The 39th International Conference on High Energy Physics (ICHEP2018)
4-11 July, 2018
Seoul, Korea

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PoS(ICHEP2018)238

1. Why search for heavy diboson resonances?

An outstanding enigma of particle physics is the hierarchy problem, i.e. the large difference between the scale of electroweak symmetry breaking and the Planck scale. Reasonings based on naturalness indicate that physics effects beyond the standard model (SM) should arise near the electroweak scale, within reach of the Large Hadron Collider (LHC). Several proposed theoretical models thus predict new resonances with masses of the order of the TeV, which can decay to pairs of W, Z, or Higgs bosons. In Randall-Sundrum models of warped extra dimensions such as the bulk graviton model, new particles can arise as Kaluza-Klein excitations of spin-2 gravitons. Some other popular extensions of the SM are described in the Heavy Vector Triplet (HVT) framework, which predicts a triplet of mass-degenerate spin-1 bosons: one neutral (Z') and two electrically charged ($\mathrm{W'}^{\pm}$). In the scenario known as HVT model B, they decay nearly exclusively to SM bosons.

The Compact Muon Solenoid (CMS) experiment [1] at the LHC has a rich search program that exploits a variety of diboson decays into quarks and leptons. An overview of such searches is given here, with results based on a data sample corresponding to an integrated luminosity of 35.9 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV, collected by the CMS detector during 2016.

2. Reconstruction and identification of boosted objects

A common feature of these searches is their boosted topology: the decay products of each considered W, Z, or Higgs boson are expected to be highly energetic and collimated, therefore requiring non-trivial identification of the final-state particles. For leptonic decays ($\mathrm{W}\to \ell\nu$, $\mathrm{Z}\to 2\ell/2\nu$), special reconstruction and isolation algorithms are applied to high-p_{T} electrons and muons, while neutrinos give rise to large missing transverse momentum. For decays to pairs of quarks, the boson is reconstructed as one single large-radius jet, which is identified via grooming and substructure techniques that are used consistently across analyses.

Jets originating from pileup interactions are suppressed using the PileUp Per Particle Identification algorithm [2], which rescales the momentum of each particle according to its compatibility with the primary interaction vertex. An infrared and collinear safe algorithm known as *soft-drop* is employed to remove of soft and large-angle radiation [3], providing the soft-drop mass variable $\mathrm{m_{jet}}$, from which signal regions and sidebands are later defined. The N-subjettiness ratio τ_2/τ_1, which discriminates two-prong jets from single quark- or gluon-initiated jets, is used to split event samples into high- and low-purity search categories. Finally, the identification of merged jets from $\mathrm{H}\to\mathrm{b\bar{b}}$ decays either relies on the CSV tagging of each subjet, or on a dedicated double-b tagger that associates secondary vertices with the two directions of subjet axes.

3. Background estimation techniques

Most searches rely on a bump hunt in the reconstructed diboson mass or transverse mass spectrum. Various background estimation strategies are used, depending on the final state.

All-hadronic searches in the $\mathrm{WW/WZ/ZZ}\to 4\mathrm{q}$ [4] and $\mathrm{WH/ZH}\to 2\mathrm{q}2\mathrm{b}$ [5] channels rely on the identification of a pair of large-radius jets, for which the dominant background is QCD multijet production. The monotonically falling spectrum of the dijet invariant mass is directly modelled from data, using a set of well-chosen analytical functions with different numbers of parameters.

A different, simulation-assisted strategy known as the α*-ratio method* is employed in several semileptonic searches, namely those in the WZ/ZZ $\to$ 2q2ν [6], the WZ/ZZ $\to$ 2q2ℓ [7], and the WH $\to$ $\ell\nu$2b and ZH $\to$ (2ν/2ℓ)2b channels [8]. These regions of the phase space are dominated by W/Z+jets backgrounds, with sizeable contributions from t$\bar{\text{t}}$ and VV processes, and are usually harder to model. The background yield in the signal region is first extracted from a fit of m_{jet} templates to data in the sidebands (Fig. 1, left), and the background diboson mass or transverse mass shapes are then interpolated from the sidebands to the signal region (Fig. 1, right).

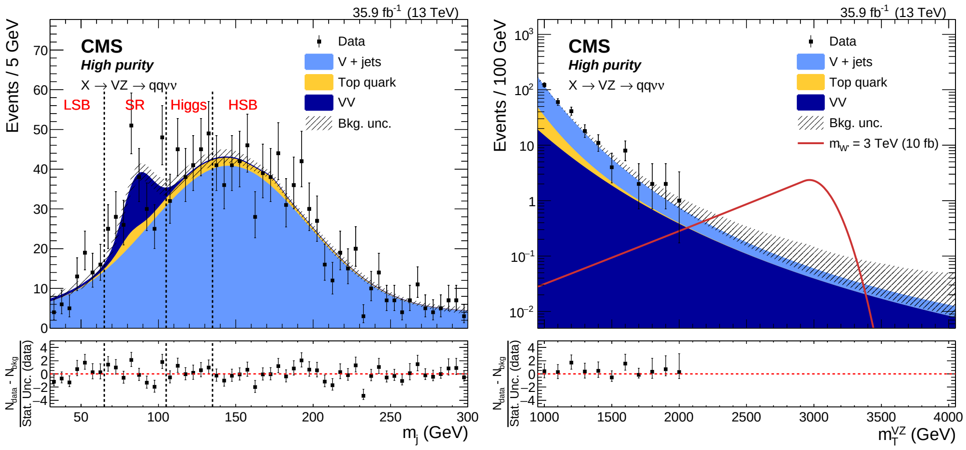

Figure 1: Results of the α-ratio method in the high-purity category for the WZ/ZZ $\to$ 2q2ν channel [6]: (left) background yield prediction in the signal region; (right) expected background shapes as a function of the transverse mass of the diboson candidate, compared to the data distribution shown as black markers.

Finally, the search in the WW/WZ $\to$ $\ell\nu$2q channel uses a novel two-dimensional (2D) fit in the plane defined by the reconstructed diboson mass and m_{jet} [9]. This largely data-driven method better exploits the statistical power of the sidebands to constrain two classes of backgrounds, either non-resonant or doubly resonant in m_{jet}. Examples of post-fit distributions are shown in Fig. 2.

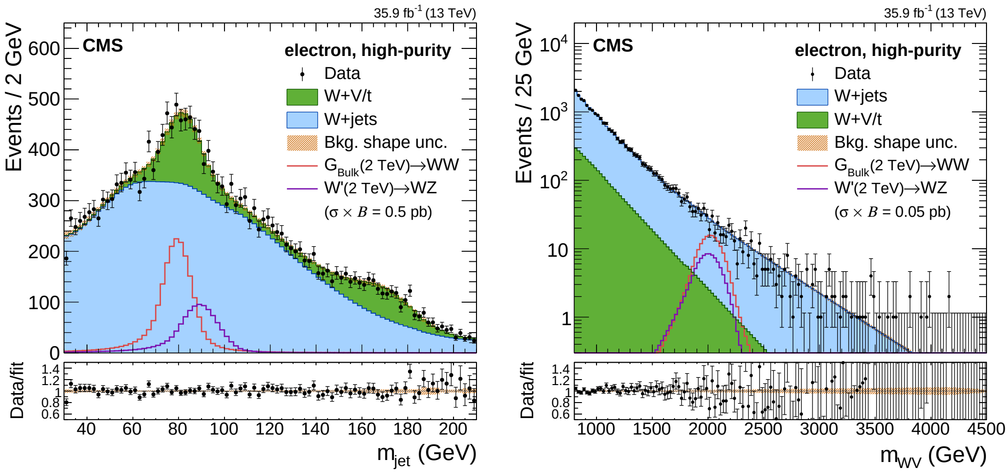

Figure 2: Results of the 2D fit in the electron high-purity category for the WW/WZ $\to$ $\ell\nu$2q channel [9], shown as post-fit projections of the background and data distributions in the soft-drop jet mass (left) and in the diboson candidate mass (right). Example signal distributions are overlaid.

4. Results and outlook

The results are interpreted in terms of 95% CL upper limits on the production cross section of either a spin-2 bulk graviton, or W' and Z' bosons of HVT model B, depending on the channel. Figure 3 presents the expected and observed limits as a function of the resonance mass hypothesis. Several of the studied decay channels exhibit comparable sensitivity, and the data are found to be consistent with background expectations. Significant future progress is expected to come from the steady improvement of analysis techniques, the inclusion of the full LHC Run 2 data sample, and the combination of decay channels.

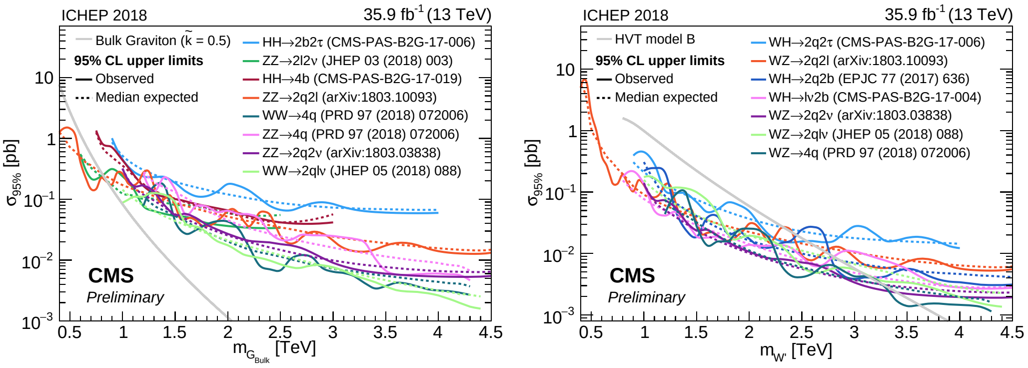

Figure 3: Summary of 95% CL upper limits on the production cross section for a spin-2 bulk graviton (left), and for a W' boson in HVT model B (right), as a function of the resonance mass, in various decay channels.

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