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Search for diboson 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. Why do we expect to see diboson resonances?

One of the most important unresolved questions of particle physics is finding an explanation why the strength of the gravitational force is many orders of magnitude weaker than the electroweak force. This is referred to as *hierarchy problem*. Furthermore, there is no symmetry in the standard model of particle physics (SM), which protects the mass of the Higgs boson. The *natural* explanation would be that the SM is replaced by another theory at the TeV scale, which is the energy scale at which the Large Hadron Collider (LHC) operates. Several theoretical models that aim to address the shortcomings of the SM therefore propose the existence of new particles with masses of $\mathscr{O}$(TeV) that could be observed in the CMS experiment [1] at the LHC.

Among the most popular scenarios are those in which gravity propagates into additional dimensions [2, 3, 4, 5], making it appear weaker in the three spatial dimensions. Several other models propose a non-fundamental nature of the Higgs boson [6, 7, 8, 9]. All of them have in common that they bring along new resonances at the TeV scale that are likely to decay to pairs of bosons.

2. Reconstructing heavy resonances

Due to the high mass of the resonances, the bosons will be very energetic, and their decay products will be very collimated. One therefore needs to develop dedicated reconstruction methods. For leptonic boson decays, this means using special isolation requirements, special reconstruction algorithms for high-p_T leptons as well as the use of new τ lepton identification algorithms. For hadronic boson decays, the key technique is the use of jet substructure, often referred to as *boson tagging* in this context.

The two main jet substructure variables that are used at CMS to distinguish boosted hadronic boson decays from quark- and gluon-initiated jets are the jet groomed mass and a variable called N-subjettiness [10]. For 2016 data, all CMS dibosons resonances analyses apply a modified mass-drop algorithm [11, 12], known as the *soft-drop* algorithm [13] to fat jets, with parameters $\beta = 0$, $z_{\text{cut}} = 0.1$, and $R_0 = 0.8$. The algorithm, like other related algorithms, removes soft and large angle radiation, but is additionally infrared and collinear safe. Overlapping proton-proton interactions within the same or nearby bunch crossings (pileup) are removed using the "PileUp Per Particle Identification" (PUPPI) algorithm [14], which yields increased pileup stability compared to the previously used algorithm [15]. The N-subjettiness is computed fixing the values of the input parameters to $\beta = 1.0$ and $R_0 = 0.8$. It quantifies to what extent the energy flow is aligned along N momentum directions. Here, the ratio of 2-subjettiness over 1-subjettiness (τ_{21}) is used to discriminate from single quark- or gluon-initiated jets. High and low purity regions are defined, where the low purity region is used to recover efficiency at high resonance masses. The variables are shown in Fig. 1.

3. Results

3.1 Run-1 legacy

All diboson resonance search results performed at a centre-of-mass energy of 8 TeV have been combined with the 2015 data results, where the LHC operated at a centre-of-mass energy of

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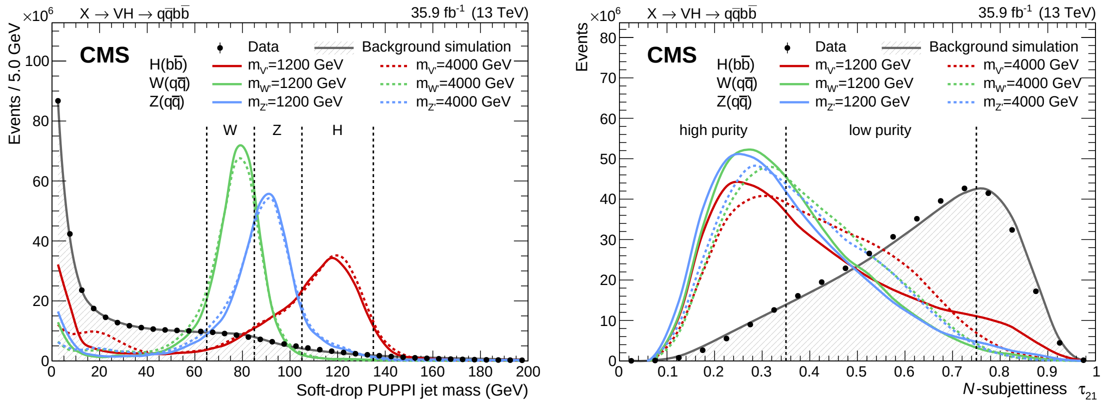


(a) (b)

Figure 1: Jet substructure variables used by CMS shown for background and for different signal mass hypotheses: (a) soft-drop jet mass, and (b) N-subjettiness ratio τ_{21}. [20]

13 TeV [16]. Results are interpreted in the heavy vector triplet (HVT) [17] models A and B (for W′, Z′, and V′ particles), in the bulk graviton model [4], and for scalar radions [18]. Limits are set over a large mass range up to 4 TeV and the combination nicely shows where which final state is most sensitive.

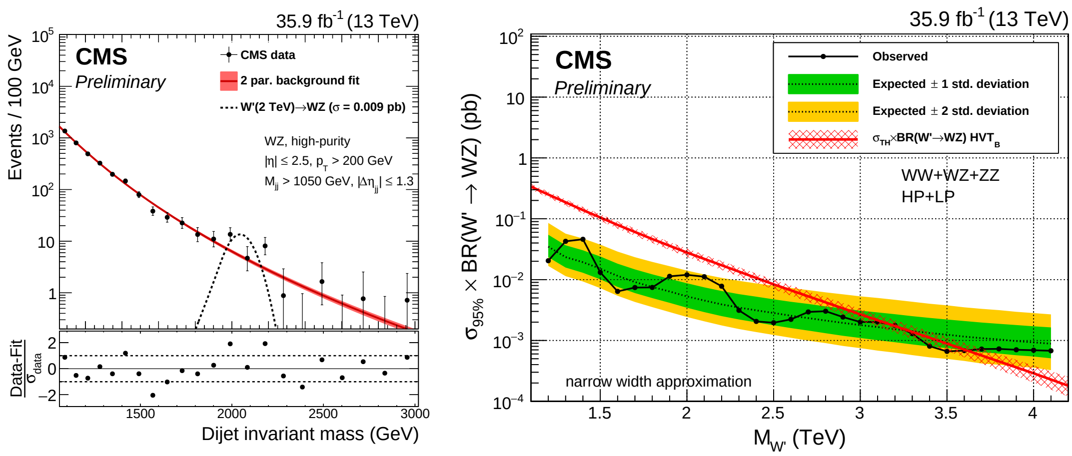
3.2 All-hadronic final state searches

The all-hadronic analyses, resulting in a dijet final state, have all in common that they make use of functional shapes to estimate the background processes, performing a so-called *bump hunt* in the invariant diboson mass spectrum. The $\mathrm{X} \to \mathrm{VV} \to 4\mathrm{q}$ and $\mathrm{q}^* \to \mathrm{qV} \to 3\mathrm{q}$ analyses [19] use a set of monotonously falling functions with different numbers of parameters. The number of parameters needed to model the background is determined directly in the signal region after extensive tests in simulation and sidebands. An example is shown in Fig. 2.

The $\mathrm{X} \to \mathrm{VH} \to 2\mathrm{q}2\mathrm{b}$ analysis [20] makes use of a dedicated boosted Higgs identification algorithm. The analysis uses the same background estimation technique as described above. The $\mathrm{X} \to \mathrm{HH} \to 4\mathrm{b}$ search [21] instead uses a new background estimation method, referred to as *alphabet-assisted (ABCDEF) bump hunt*. This method allows to additionally constrain the background normalisation in a jet mass sideband region when performing the functional shape fit. None of the analyses show any significant excess over the SM expectation. Upper cross section limits are set over a large mass range exceeding the reach of the previously performed analyses.

3.3 Final state searches with $\mathrm{Z} \to \nu\nu$ decays

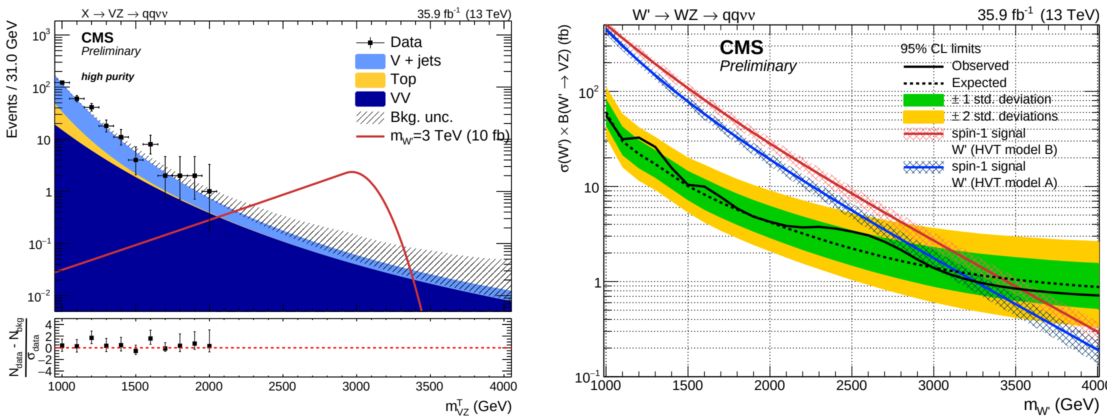
The public 2016 data analyses exploiting final states containing Z bosons decaying to neutrinos are the $\mathrm{X} \to \mathrm{ZZ} \to 2\ell 2\nu$ [22] and the $\mathrm{X} \to \mathrm{VZ} \to 2\mathrm{q}2\nu$ [23] searches. Since neutrinos can only be identified indirectly in the detector as missing transverse momentum, the variable of interest here is the diboson transverse mass. The $\mathrm{X} \to \mathrm{ZZ} \to 2\ell 2\nu$ search relies mostly on SM background templates taken from simulation, but the dominant Drell-Yan+jets background is estimated using data from γ+jets events corrected for differences between the two processes. The $\mathrm{X} \to \mathrm{VZ} \to 2\mathrm{q}2\nu$ uses a background estimation method that has been widely used in the semileptonic 2012 and



(a) (b)

Figure 2: (a) Dijet invariant mass spectrum of the $X \to VV \to 4q$ analysis in the WZ high-purity category fit with a monotonously falling function, and (b) resulting upper cross section limits on $W' \to WZ$ production as a function of resonance mass combining all categories. [19]

2015 data diboson analyses, the simulation-assisted *alpha-ratio method*. It exploits the correlation between the soft-drop jet mass and the resonance mass, taking the ratio of simulation to data in the jet mass sideband and extrapolating it to the signal region. A resulting spectrum and corresponding limits are shown in Fig. 3. The two analyses do not show significant deviations from the background expectation, and limits on the production cross sections are set.



(a) (b)

Figure 3: (a) Transverse invariant diboson mass spectrum of the $X \to VZ \to 2q2\nu$ analysis in the WZ high-purity category, and (b) resulting upper cross section limits on $W' \to WZ$ production as a function of resonance mass combining all categories. [23]

4. Summary and outlook

CMS has already covered a large number of final states in its diboson resonance search programme using the full 2016 data set. No significant deviations from the SM background expectation have been observed. Further final states are being explored, and it is planned to refine the analyses to make significant progress using 2017+2018 collision data.

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