Searches for new resonances decaying to $W$, $Z$ and $H$ bosons with the ATLAS and CMS detectors in 13 TeV proton-proton collisions at the LHC

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ABSTRACT

Searches for high-mass resonances decaying to pairs of standard model bosons using ATLAS and CMS detectors are presented. The searches use 15 - 36 fb$^{-1}$ of proton-proton collision data collected at the centre-of-mass energy of 13 TeV at the LHC. Many different final states have been considered and the results are interpreted in a range of theories beyond the standard model of particle physics, most common being heavy vector triplet and warped extra dimensions.

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1 Introduction

Many theories of physics beyond the standard model (BSM) predict the existence of new heavy particles that decay to pairs of standard model (SM) bosons, either vector bosons (V), being W and Z, or the Higgs boson (H). BSM models most commonly used for the interpretation of the results are the heavy vector triplet (HVT) [3] and bulk Randall-Sundrum (RS) scenario of warped extra dimensions [4]. HVT is a simplified model used to describe the phenomenology of new spin-1 resonances (W' and Z') with a small number of parameters. An interesting case for this report is the so-called scenario B where the fermionic couplings are suppressed and decays to bosons dominate. In the bulk scenario of the Randall-Sundrum model, all the SM fields, along with the spin-2 graviton, are allowed to propagate in the warped extra dimension. In this RS scenario the couplings of the graviton to light fermions are suppressed (and the coupling to photons negligible) making decays to dibosons a highly motivated case. The searches for high mass VH, VV and HH resonances have been performed in a large number of final states, however, this report focuses only on a couple of recent analyses with 15-36 fb$^{-1}$ of the 13 TeV ATLAS [1] and CMS [2] datasets.

2 Common analysis techniques

Standard model bosons emerging from the decays of a heavy BSM state (where heavy means having a mass much larger than the mass scale of SM states) are often highly boosted. If the momentum of the SM boson is sufficiently high, the angular separation between its hadronic decay products will be smaller than angular size typically used by the experiments for the jet reconstruction, resulting in the boson being reconstructed as a single large radius (fat) jet. ATLAS and CMS have developed sophisticated techniques for reconstructing and tagging such boosted states. Jet grooming is used to remove soft and large angle QCD radiation and pile-up contributions, and to improve the resolution of V/H-jet mass. Jet substructure and tagging techniques are then used to further discriminate between the background quark/gluon-initiated jets and signal V/H-jets.

2.1 Jet grooming

ATLAS reconstructs fat jets using topological clusters as the input to the anti-kT algorithm with the angular parameter R=1.0. A trimming technique [5] is used to remove the pileup contamination – jet constituents are reclustered into subjets with R=0.2 and all the subjets satisfying the condition $p_T^{(\text{subjet})}/p_T^{(\text{jet})} < 0.05$ are removed. Jet mass is then computed using information from both the calorimeter and the tracks associated with the jet [6].

CMS reconstructs particle-flow jets using the anti-kT algorithm with the angular parameter R=0.8. Pileup per particle identification [7] algorithm uses a weight assigned to each particle based on its likelihood to originate from pileup interactions to rescale the particle 4-momenta. A modified mass-drop algorithm, referred to as soft-drop algorithm [8, 9, 10], iteratively breaks the jet into 2 sub-jets and drops the softer one until the soft-drop condition is satisfied [11]. This procedure improves the resolution in the V jet mass, lowers the mass of quark/gluon-initiated jets from multijet background and further reduces the pileup contamination.

2.2 Boosted boson tagging

ATLAS tags Higgs boson decays to two b-quarks by requiring one or two b-tagged track jets (R=0.2) associated to a fat jet consistent with the Higgs boson mass. Boosted W/Z-boson candidates are required to have their mass consistent with the W/Z-mass within window size ranging between 15 GeV and 40 GeV, depending on the analysis. The ratio of energy correlation functions $D_2^{\beta=1}$ [12, 13] is used to test the compatibility with a two-prong decay topology of the fat jet. Transverse momentum dependent selection on the $D_2^{\beta=1}$ variable is applied with the approximate V-tagging efficiency of 50% and quark/gluon-jet mistag efficiency of 2%.
CMS uses a dedicated b-tagging discriminator to identify two b-quarks clustered in a single jet with mass consistent to that of the Higgs boson. Boosted V-candidates are required to have their mass consistent either with W (65 GeV – 85 GeV) or Z (85 GeV – 105 GeV) mass. The ratio of N-subjettiness $\tau_{21} = \tau_2/\tau_1$, that quantify the capability of reclustering the jet constituents in exactly two ($\tau_2$) or one ($\tau_1$) subjets is used to assess the compatibility with a two-prong decay.

3 \textbf{VH} \rightarrow \textbf{qqbb}

ATLAS analysis [15] searches for a resonance in the invariant mass spectrum of two fat jets, $m_{JJ}$. Four search regions are defined based on the number of b-tagged track jets associated with H-candidate and the mass of the V-candidate. The dominant multijet background is estimated using a template extracted from the data in the region with zero b-tagged track jets associated to the H-candidate. The template is corrected with kinematic reweighting in order to correctly reproduce the kinematics of the search region and validated in the V-mass sidebands. Upper limits are set on the production cross section times the branching ratio to VH($H$→heavy-flavour jets) final states in the $1 < m_{JJ} < 3$ TeV region (Fig. 1 left). The biggest discrepancy between the SM expectation and the observed data is found at $m_{JJ} \sim 3$ TeV and has the global significance of 2.2 $\sigma$.

The corresponding CMS analysis [18] considers eight exclusive search regions depending on the V-jet mass, H-jet b-tagging discriminator and $\tau_{21}$ value for V-jets. The dominant multijet background is extracted in a fit to the data with an analytic function and validated in the V-mass sidebands. Limits are set in $1 < m_{JJ} < 4.5$ TeV region (Fig. 1 right). No significant excess is found.

Figure 1: Observed (solid black) and expected (dashed) limits at 95% CL on the cross section times branching ratio for the $W'\rightarrow WH$ search in ATLAS (left) [15] and CMS (right) [18]. The red and magenta curves show the predicted cross-sections as a function of resonance mass for the A and B scenarios of the HVT model.

4 \textbf{VV} \rightarrow \textbf{qqqq}

Searches for a WW/WZ/ZZ resonance in a fully hadronic final state have been performed in both ATLAS [16] and CMS [19] using techniques and event categorizations very similar to the ones used in VH searches in Sec. 3. The multijet background is modelled with a parametric function and validated in the sidebands of the V-candidate mass. No significant excess is found and upper limits are set on production cross section times the branching ratio to VV final states in $1.2 < m_{JJ} < 3$ TeV ($1.2 < m_{JJ} < 4.2$ TeV) range by ATLAS (CMS) (Fig. 2).
Figure 2: Observed (solid black) and expected (dashed) limits at 95% CL on the cross section times branching ratio for the $W' \rightarrow WZ$ search in ATLAS (left) and CMS (right). The red and magenta curves show the predicted cross-sections as a function of resonance mass for the HVT model.

5 $ZZ \rightarrow 2\ell 2\nu$

This CMS search [21] profits from a large branching ratio of $ZZ$ to $2\ell 2\nu$ (where $\ell = e$ or $\mu$) final state and controllable backgrounds. The main discriminating variable is the transverse mass ($M_T$) of the two leptons and missing transverse momentum (denoted as $E_T^{\text{miss}}$), where a Jacobian edge from a potential resonance would be expected in the distribution (Fig. 3 left). The dominant background process is $Z+$jets production in which $E_T^{\text{miss}}$ comes from mismeasurements of jet or lepton momenta. It is estimated from a $\gamma+$jets data sample reweighted to reproduce the kinematics of $Z+$jets events. The limits on $\sigma(X \rightarrow ZZ)$ are presented in Fig. 3 (right).

Figure 3: Left: The $M_T$ distribution for the electron channel in the search region comparing data and data-driven background modelling. Right: Observed (thick blue) and expected (thin blue) limits at 95% CL on the cross section times branching ratio for the $X \rightarrow ZZ$ search in CMS [21].
6 HH → 4b

The ATLAS search for a di-Higgs resonance \[17\] considers both the resolved regime, where four b-tagged jets with R=0.4 can be reconstructed, and the boosted regime, where two fat H-tagged jets are reconstructed. The resolved analysis provides better sensitivity in the low-mass region, where the reconstructed Higgs mass \(m_{HH}\) is below 1 TeV, while the boosted analysis performs better at \(m_{HH} > 1\) TeV. The dominant multijet background is modelled using an independent data sample – from a region with exactly two b-tagged jets (instead of at least four in the search region) in the resolved case and from a region where none of the track jets associated to a H-candidate were b-tagged in the boosted case. The upper limits on the production cross section times the branching ratio are set in the context of the bulk Kaluza-Klein graviton \(G_{KK}^*\) and shown in Fig. 4 (left).

The CMS analysis \[20\] requires two H-tagged fat jets with \(M_{JJ} > 750\) GeV. Events are separated into two categories depending on the double-b-tag discriminator: events with tighter b-tagging criteria having higher purity, but lower signal efficiency, and events with looser b-tagging criteria and correspondingly lower purity but higher signal efficiency. The dominant multijet background is estimated using the data from the region with the inverted value of the b-tag discriminator. No significant excess is observed and limits are set on the product of the production cross section and the branching ratio in the 750 < \(M_{JJ} < 3000\) GeV range (Fig. 4, right).

![Figure 4: Observed (solid black) and expected (dashed) limits at 95% CL on the cross section times branching ratio for the X→ HH search in ATLAS (left) \[17\] and CMS (right) \[20\]. The red curves show the predicted cross-sections as a function of resonance mass for the bulk Randall-Sundrum model.](image)

7 Conclusions

Extensive searches for high-mass diboson resonances have been performed both in ATLAS and CMS. So far no significant discrepancy has been found between the observed data and the SM expectation. The largest deviation from the background-only hypothesis has been seen in the ATLAS \(VH\rightarrow q\bar{q}bb\) search at \(m_{VH} \sim 3\) TeV and has the global significance of \(\sim 2.2\) \(\sigma\). The excess has not been observed in the corresponding CMS analysis.

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