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Search for diboson resonances with jets in 20.3 fb^{-1} pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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A search for narrow diboson high mass resonances in a dijet final state is performed in 20.3 fb^{-1} of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV, collected in 2012 by the ATLAS detector at the Large Hadron Collider [1]. The jet mass and jet substructure properties have been used to tag each jet as a boson. Using the invariant mass distribution of the boson tagged dijet system, 95 % CL exclusion limits are set on the production cross section times branching ratio to WW, WZ, or ZZ final states of W' Extended Gauge Model bosons and Kaluza-Klein excitations of the graviton in the bulk Randall-Sundrum model, as a function of the resonance mass. The observed mass distributions exhibit an excess of events above 1.8 TeV.

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1. Introduction

This search is based on proton-proton (pp) collision data collected by the ATLAS experiment [2] at the Large Hadron Collider (LHC) in 2012. These data correspond to an integrated luminosity of 20.3 fb^{-1} collected at a center of mass energy of 8 TeV. This dataset provides a distinct opportunity to search for new heavy resonances at the TeV mass scale. The analysis is focused on the search for narrow diboson resonances (WW, WZ and ZZ) decaying to fully hadronic final states. The fully hadronic mode has a higher branching fraction than leptonic and semileptonic decay modes, and is therefore used to extend the reach of the search to the highest possible resonance masses.

W and Z bosons resulting from the decay of very massive resonances are highly boosted, so that each boson's hadronic decay products are reconstructed as a single jet. The signature of the heavy resonance decay is thus a resonance structure in the dijet invariant mass spectrum. The dominant background for this search is due to dijet events from QCD processes, which produce a smoothly falling spectrum without resonance structure.

Diboson resonances are predicted in several extensions to the SM, such as technicolour [3, 4, 5], warped extra dimensions [6, 7, 8], and Grand Unified Theories [9, 10, 11, 12]. To assess the sensitivity of the search, to optimise the event selection, and for comparison with data, two specific benchmark models are used: an extended gauge model (EGM) $W' \rightarrow WZ$ where the spin-1 W' gauge boson has a modified coupling to the SM W and Z bosons [13, 14, 15], and a Kaluza–Klein excitation of the spin-2 graviton [6, 16] , $G_{RS} \rightarrow WW$ or ZZ, as predicted in the bulk Randall–Sundrum (RS) model [17, 18, 19].

2. ATLAS collision data

A three-level trigger system is used in ATLAS to reduce the LHC event rate to a few hundred Hz. Events used in this search satisfy a single-jet trigger requirement, based on at least one jet reconstructed at each trigger level. At the first filtering stage of the high-level trigger, jet candidates are reconstructed from calorimeter cells using a cone algorithm with small radius, R=0.4. The final filter in the high-level trigger requires a jet to satisfy a higher transverse momentum (p_T) threshold of 360 GeV, reconstructed with the anti-k_t algorithm [20] and a large radius parameter (R=1.0).

The full 8 TeV LHC pp collision dataset has been used for this search, and its integrated luminosity after requiring good beam and detector conditions is 20.3 fb^{-1}, with a relative uncertainty of $\pm$2.8% [21].

3. Simulated signal and background samples

The leading-order Monte Carlo generator PYTHIA 8.170 [22] is used to model $W' \rightarrow WZ$ events in order to determine and optimise the sensitivity of this search. The W' boson samples are generated assuming EGM couplings [13] for the W'. It is required to decay to a W and a Z boson, which are both forced to decay hadronically. The samples generated for this analysis use MSTW2008 [23] parton distribution functions (PDFs), with parton shower parameters tuned to ATLAS underlying-event data [24]. An additional set of W' samples generated with PYTHIA for the hard scattering interaction and HERWIG++ [25] for parton showering and hadronisation is used to assess systematic uncertainties on the signal efficiency due to uncertainties on the parton shower and hadronisation model.

An extended RS model with a warped extra dimension is used for the excited graviton benchmarks [17]. The RS excited graviton samples are generated with CalcHEP 3.4 [26] setting the dimensionless coupling constant $k/\bar{M}_{\text{Pl}} = 1$[1]. The graviton resonance is decayed to WW or ZZ, and the resulting W or Z bosons are forced to decay hadronically. The cross section times branching ratio as well as the resonance width are by CalcHEP for the RS. Events are generated using CTEQ6L1 [27] PDFs, and use PYTHIA 8 for the parton shower and hadronisation.

To characterise the expected dijet invariant mass spectrum in the mass range 1.3–3.0 TeV, simulated QCD dijet events, diboson events, and single W or Z bosons produced with jets are used. Contributions from SM diboson events are expected to account for approximately 6% of the selected sample, and single boson production is expected to contribute less than 2%. Contributions from $t\bar{t}$ production, studied using MC@NLO [28] and HERWIG [29] showering, were found to be negligible and are not considered further. Both QCD dijet events and W/Z+jets samples are produced with PYTHIA 8 using CT10 [30] and CTEQ6L1 PDFs, respectively. Diboson events are produced at the generator level with POWHEG [31], using PYTHIA for the soft parton shower.

For all the generated samples, the contribution from additional minimum-bias pp interactions is accounted for by overlaying additional minimum-bias events generated with PYTHIA 8, matching the distribution of the number of interactions per bunch crossing observed in collision data.

4. Boson jet identification and event selection

The dominant background for this search is due to di-jet events from QCD processes. W and Z bosons from the decay of the massive resonance are produced with a large transverse momentum relative to their mass and each boson is reconstructed as a single large-radius jet. The application of jet substructure for jet grooming and boson tagging on the two highest p_{T} identified jets in the events is able to significantly suppress the huge QCD di-jet background. Jets are reconstructed using Cambridge–Aachen (C/A) algorithm [32, 33] with a radius parameter $R = 1.2$. To reduce the effect of pileup and other noise sources on the resolution, and to identify pair of subjets associated with the hadronic boson decay, a modified version of the canonical BDRS [34] split-filtering method, the BDRS-A, has been implemented. The main parameters of the BDRS algorithm are the *mass-drop*[2], μ_{filt}, and the *subjet momentum balance*[3], $\sqrt{y_{filt}}$. BDRS-A has been optimized in order to identify and measure boson jets with transverse momentum larger than 0.5 TeV. The parameters used in this analysis are: $\mu_{filt} = 1$, corresponding to no mass-drop requirement being imposed in the grooming procedure; $\sqrt{y_{filt}} = 0.2$; $R_{\text{r}} = 0.3$, the small radius distance parameter used to recluster the identified subjets, and $n_{\text{r}} = 3$, corresponding to the number of highest-p_{T} subjets that are kept during the jet filtering procedure.

[1] The k parameter is the curvature of the warped extra dimension and $\bar{M}_{\text{Pl}}$ is the reduced Planck mass

[2] The mass-drop, μ, is defined as $\mu \equiv m_i/m_0$, where m_0 is the mass of the parent jet, and m_i is the mass of the subjects identified examining the the sequence of pairwise combinations used to reconstruct the jet in reverse order.

[3] The subjet momentum balance is defined as $\sqrt{y} \equiv \min(p_{\text{T}\,j_1}, p_{\text{T}\,j_2}) \frac{\Delta R_{(j_1,j_2)}}{m_0}$, where $\min(p_{\text{T}\,j_1}, p_{\text{T}\,j_2})$ and $\Delta R_{(j_1,j_2)}$ are respectively the lowest transfers momentum and the angular distance between the two subjets.

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In addition to the grooming procedure, and in order to increase the separation between signal and background jets, the following variables have been used to perform the boson tagging on the groomed jets:

jet mass Jets from W and Z bosons are expected to have mass peaks near 80 and 91 GeV, respectively, while those from QCD sources are expected to have smoother distributions. In order to distinguish between WZ, WW and ZZ final states, different jet mass window cuts have been defined for W and Z bosons.

sub-jets momentum balance, $\sqrt{y_f}$ It is approximately the ratio of the lower and higher p_T values of the two sub-jets and it measures the level of balancing inside the jet constituents. It peaks sharply near zero for background coming from gluon radiation, while shows a flat distribution extending up to one for longitudinal bosons, where the rest-frame quarks are emitted perpendicularly to the boson's direction of motion.

Number of tracks associated to the unfiltered jet Energetic gluon emissions tend to create jets with large hadron multiplicity. Cutting on this variable rejects background events with hard gluons that may pass the $\sqrt{y_f}$ cut.

Together with the tagging cuts, kinematic cuts, such as rapidity gap between the two leading jets smaller than 1.2 and a cut on jet pseudo-rapidity ($|\eta|< 2$), have been applied on the dijet system in order to select central events produced by s-channel processes.

5. Background model and systematic uncertainties

The search for high-mass diboson resonances is carried out by looking for resonance structures on a smoothly falling dijet invariant mass spectrum, empirically characterised by the function

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2+\xi p_3}x^{p_3}, \tag{5.1}$$

where $x = m_{jj}/\sqrt{s}$, and m_{jj} is the dijet invariant mass, p_1 is a normalisation factor, p_2 and p_3 are dimensionless shape parameters, and ξ is a dimensionless constant chosen after fitting to minimise the correlations between p_2 and p_3. A binned maximum-likelihood fit, with parameters p_1, p_2 and p_3 free to float, is performed in the range 1.05 TeV $< m_{jj} <$ 3.55 TeV, where the lower limit is dictated by the point where the trigger is fully efficient for tagged jets and the upper limit is set to be in a region where the data and the background estimated by the fit are well below one event per bin for the tagged distributions.
The uncertainty on the background expectation has been determined by the fitting procedure, assuming a smoothly falling distribution versus the di-jet invariant mass. All the possible sources of uncertainty due to the background model, such as that on the trigger efficiency, on the variation of the selection efficiency as a function of the kinematic properties of the background, and the one on background composition, were studied and found to be well-covered by the uncertainties from the fitting procedure.

The shape and normalization uncertainties on the signal are taken into account as nuisance parameters with specified probability distribution functions. They have been derived using the calo-track double ratio technique. This relies on the ability to reconstruct jets using both topological clusters from the calorimeter (calo-jets) and tracks from the inner detector (track-jets). The comparison of two measurements of the same object, performed with two separate subsystem of ATLAS, is able to cancel out any theoretical uncertainty, while pointing out any systematic mismodelling in the detector simulation. Table 1 summarises the systematic uncertainties affecting the signal shape and the pdf constraining the associated nuisance parameter, while table 2 summarises the systematic uncertainties affecting the signal normalisation.

Source	Uncertainty	Constraining pdf
Jet p_{T} scale	2%	$G(\alpha_{\mathrm{PT}}\|1,0.02)$
Jet p_{T} resolution	20%	$G(\sigma_{r_E}\|0,0.05\times\sqrt{1.2^2-1^2})$
Jet mass scale	3%	$G(\alpha_{\mathrm{m}}\|1,0.03)$

Table 1: Summary of the systematic uncertainties affecting the shape of the signal dijet mass distribution and their corresponding models. $G(x|\mu,\sigma)$ in the table denotes a Gaussian distribution for the variable x with mean μ and standard deviation σ [1].

Source	Normalisation uncertainty
Efficiency of the track-multiplicity cut	20.0%
Jet mass scale	5.0%
Jet mass resolution	5.5%
Subjet momentum-balance scale	3.5%
Subjet momentum-balance resolution	2.0%
Parton shower model	5.0%
Parton distribution functions	3.5%
Luminosity	2.8%

Table 2: Summary of the systematic uncertainties affecting the signal normalisation and their impact on the signal [1].

6. Results

The fitting procedure is applied to the data after WZ, WW and ZZ selection, and the results are shown in figure 1. In this figure, the fitted background functions, labelled "background model," are again integrated over the same bins used to display the data, and the size of the shaded band reflects the uncertainties on the parameters propagated to show the uncertainty on the expectation from the fit. The lower panels in the figure show the significance of the difference between data and the expectation in each bin. Figure 1 shows the background-only fits to the dijet mass (m_{jj}) distributions in data after the WZ, WW and ZZ selections.

In the region around 2 TeV in dijet mass, the Run 1 data shows an excess of events with respect to the background expectation. The WZ selected spectra shows the most discrepant distribution from the background only hypothesis, leading to a local significance of 3.4 standard deviations. Taking into account the look-elsewhere-effect (LEE) and the correlations between the three selected spectra, the global significance of the excess is 2.5 standard deviations.

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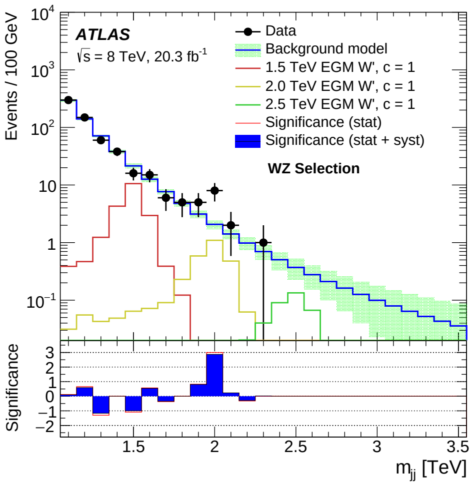
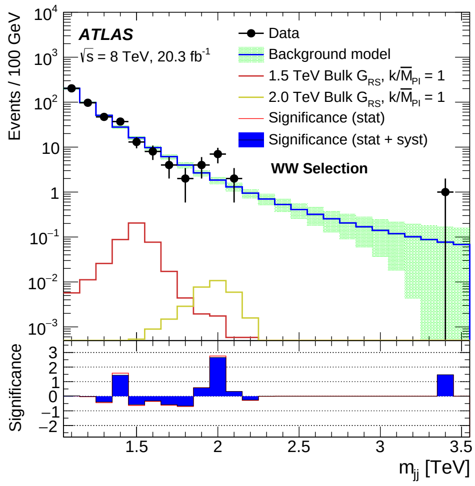
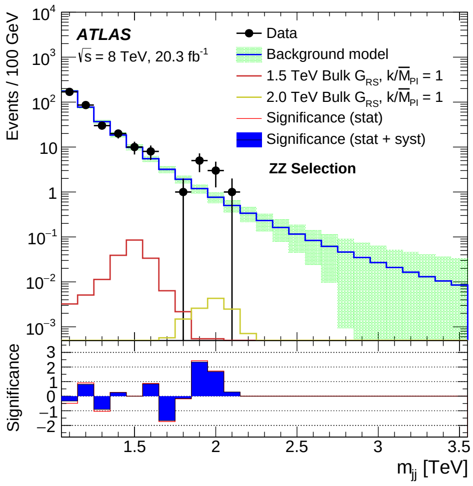


(a)



(b)



(c)

Figure 1: Background-only fits to the dijet mass (m_{jj}) distributions in data (a) after tagging with the WZ selection, (b) after tagging with the WW selection and (c) after tagging with the ZZ selection. The significance shown in the inset for each bin is the difference between the data and the fit in units of the uncertainty on this difference. The significance with respect to the maximum-likelihood expectation is displayed in red, and the significance when taking the uncertainties on the fit parameters into account is shown in blue. The spectra are compared to the signals expected for an EGM W' with $m_{W'}$ = 1.5, 2.0, or 2.5 TeV or to an RS graviton with $m_{G_{RS}}$ = 1.5 or 2.0 TeV [1].

Using the CLs prescription [35], upper limits on the production cross section times branching ratio of massive resonances have been set in each diboson channel as a function of the resonance mass, using EGM $W' \to WZ$ as a benchmark for the WZ channel, and an excited bulk graviton G_{RS} to represent resonances decaying to WW and ZZ. The search was able to exclude W' with masses between 1.3 and 1.5 TeV for a W' with EGM coupling.

7. Conclusions

A search has been performed for massive particles decaying to WW, WZ, or ZZ using 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data collected at the LHC by ATLAS in 2012. This is the first ATLAS search for resonant diboson production in a fully hadronic final state and strongly relies on the suppression of the dijet background with a substructure-based jet grooming and boson tagging procedure. The most significant discrepancy with the background-only model occurs around 2 TeV in the WZ channel with a local significance of 3.4 σ and a global significance of 2.5 σ. Upper limits on the production cross section times branching ratio of massive resonances are set in each diboson channel as a function of the resonance mass, using an EGM $W' \to WZ$ as a benchmark for the WZ channel, and an excited bulk graviton G_{RS} to represent resonances decaying to WW and ZZ. A W' with EGM couplings and mass between 1.3 and 1.5 TeV is excluded at 95% CL.

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