EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Phys. Lett. B.

CERN-PH-EP-2015-269
31st March 2016

Combination of searches for WW, WZ, and ZZ resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

The ATLAS experiment at the CERN Large Hadron Collider has performed searches for new, heavy bosons decaying to WW, WZ and ZZ final states in multiple decay channels using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV. In the current study, the results of these searches are combined to provide a more stringent test of models predicting heavy resonances with couplings to vector bosons. Direct searches for a charged diboson resonance decaying to WZ in the $\ell\nu\ell'\ell'$ ($\ell = \mu, e$) , $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and fully hadronic final states are combined and upper limits on the rate of production times branching ratio to the WZ bosons are compared with predictions of an extended gauge model with a heavy W' boson. In addition, direct searches for a neutral diboson resonance decaying to WW and ZZ in the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and fully hadronic final states are combined and upper limits on the rate of production times branching ratio to the WW and ZZ bosons are compared with predictions for a heavy, spin-2 graviton in an extended Randall–Sundrum model where the Standard Model fields are allowed to propagate in the bulk of the extra dimension.

Contents

1 Introduction

The naturalness argument associated with the small mass of the recently discovered Higgs boson [1–4] suggests that the Standard Model (SM) is conceivably to be extended by a theory that includes additional particles and interactions at the TeV scale. Many such extensions of the SM, such as extended gauge models [5–7], models of warped extra dimensions [8–10], technicolour [11–14], and more generic composite Higgs models [15, 16], predict the existence of massive resonances decaying to pairs of W and Z bosons.

In the extended gauge model (EGM) [5] a new, charged vector boson (W') couples to the SM particles. The coupling between the W' and the SM fermions is the same as the coupling between the W boson and the SM fermions. The $W'WZ$ coupling has the same structure as the WWZ coupling in the SM, but is scaled by a factor $c \times (m_W/m_{W'})^2$, where c is a scaling constant, m_W is the W boson mass, and $m_{W'}$ is the W' boson mass. The scaling of the coupling allows the width of the W' boson to increase approximately linearly with $m_{W'}$ at $m_{W'} \gg m_W$ and to remain narrow for $c \sim 1$. For $c = 1$ and $m_{W'} > 0.5$ TeV the W' width is approximately 3.6% of its mass and the branching ratio of the $W' \to WZ$ ranges from 1.6% to 1.2% depending on $m_{W'}$. Production cross sections in pp collisions at $\sqrt{s} = 8$ TeV for the W' boson as well as the W' width and branching ratios of $W' \to WZ$ for a selection of W' boson masses in the EGM with scale factor $c = 1$ are given in Table 1.

Searches for a W' boson decaying to $\ell\nu$ have set strong bounds on the mass of the W' when assuming the sequential standard model (SSM) [17, 18], which differs from the EGM in that the $W'WZ$ coupling is set to zero. For $c \sim 1$ the effect of this coupling on the production cross section of the W' boson at the LHC is very small, thus the production cross section of the W' boson in the SSM and the EGM is very similar. Moreover, due to the small branching ratio of the $W' \to WZ$ in the EGM with the scale factor $c \sim 1$, the branching ratios of the W' boson to fermions are approximately the same as in the SSM. Nevertheless, models with narrow vector resonances with suppressed fermionic couplings remain viable extensions to the SM, and thus the EGM provides a useful and simple benchmark in searches for narrow vector resonances decaying to WZ.

The ATLAS and CMS collaborations have set exclusion bounds on the production and decay of the EGM W' boson. In searches using the $\ell\nu\ell'\ell'$ ($\ell \equiv e, \mu$) channel, the ATLAS [19] and CMS [20] collaborations have excluded, at the 95% confidence level (CL), EGM ($c = 1$) W' bosons decaying to WZ for W' masses below 1.52 TeV and 1.55 TeV, respectively. In addition the ATLAS Collaboration has excluded EGM ($c = 1$) W' bosons for masses below 1.59 TeV using the $\ell\ell q\bar{q}$ [21] channel, and below 1.49 TeV using the $\ell\nu q\bar{q}$ [22] channel. These have also been excluded with masses between 1.3 and 1.5 TeV and below 1.7 TeV by the ATLAS [23] and CMS [24] collaborations, respectively, using the fully hadronic final state.

Diboson resonances are also predicted in an extension of the original Randall–Sundrum (RS) [8–10] model with a warped extra dimension. In this extension to the RS model [25–27], the SM fields are allowed to propagate in the bulk of the extra dimension, avoiding constraints on the original RS model from flavour-changing neutral currents and from electroweak precision measurements. This so-called bulk-RS model is characterized by a dimensionless coupling constant $k/\bar{M}_{\mathrm{Pl}} \sim 1$, where k is the curvature of the warped extra dimension, and $\bar{M}_{\mathrm{Pl}} = M_{\mathrm{Pl}}/\sqrt{8\pi}$ is the reduced Planck mass. In this model a Kaluza–Klein excitation of the spin-2 graviton, G^*, can decay to pairs of W or Z bosons. For bulk RS models with $k/\bar{M}_{\mathrm{Pl}} = 1$ and for G^* masses between 0.5 and 2.5 TeV, the branching ratio of G^* to WW ranges from 34% to 16% and the branching ratio to ZZ ranges from 18% to 8%. The G^* width ranges from 3.7% to 6.2% depending on the G^* mass. Table 1 lists widths, branching ratio to WW and ZZ for G^*, and production cross sections in pp collisions at 8 TeV in these bulk RS models.

The ATLAS Collaboration has excluded, at the 95% CL, bulk $G^* \to ZZ$ with masses below 740 GeV, using the $\ell\ell q\bar{q}$ channel [21], as well as bulk $G^* \to WW$ with masses below 760 GeV, using the $\ell\nu q\bar{q}$ channel assuming $k/\bar{M}_{\mathrm{Pl}} = 1$ [22]. The CMS Collaboration has also excluded at the 95% CL the G^* of the original RS model, decaying to WW and ZZ with masses below 1.2 TeV using the fully hadronic final state [24] and has set limits on the production and decay of generic diboson resonances using a combination of $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and fully hadronic final states [28].

To improve the sensitivity to new diboson resonances, this article presents a combination of four statistically independent searches for diboson resonances previously published by the ATLAS Collaboration [19, 21–23]. The searches are combined while considering the correlations between systematic uncertainties in the different channels. The first search, sensitive to charged resonances decaying to WZ, uses the $\ell\nu\ell'\ell'$ [19] final state. The second search, sensitive to charged resonances decaying to WZ and neutral resonances decaying to ZZ, uses the $\ell\ell q\bar{q}$ final state [21]. The third search, sensitive to charged resonances decaying to WZ and neutral resonances decaying to WW, uses the $\ell\nu q\bar{q}$ final state [22]. Finally, the fourth search, sensitive to charged resonances decaying to WZ and to neutral resonances decaying to either WW or ZZ, uses the fully hadronic final state [23]. Due to the large momenta of the bosons from the resonance decay, the resonance in this channel is reconstructed with two large-radius jets, and the fully hadronic channel is hereafter referred to as the JJ channel.

To search for a charged diboson resonance decaying to WZ the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels are combined. The result of this combination is interpreted using the EGM W' model with $c = 1$ as a benchmark.

To search for neutral diboson resonances decaying to WW and ZZ the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels are combined, and the result is interpreted using the bulk G^*, assuming $k/\bar{M}_{\mathrm{Pl}} = 1$, as a benchmark.

The ATLAS Collaboration has performed additional searches in which new diboson resonances could manifest themselves as excesses over the background expectation. In the analysis presented in Ref. [29] the $\ell\ell\ell'\ell'$, $\ell\ell\nu\nu$, $\ell\ell q\bar{q}$ and $q\bar{q}\nu\nu$ final states have been explored in the context of the search for a new, heavy Higgs boson. Also, in the context of searches for dark matter a final state of a hadronically decaying boson and missing transverse momentum [30], and a final state of a leptonically decaying Z boson and missing transverse momentum have been explored [31]. These additional searches are not included in this combination. They are not expected to contribute significantly to the sensitivity of the combined search due to the lower branching ratio in case of the leptonic channels, and the use of only narrow jets in case of the $q\bar{q}\nu\nu$ final state.

2 ATLAS detector and data sample

The ATLAS detector is described in detail in Ref. [32]. It covers nearly the entire solid angle [1] around the interaction point and has an approximately cylindrical geometry. It consists of an inner tracking detector (ID) placed within a 2 T axial magnetic field surrounded by electromagnetic and hadronic calorimeters and followed by a muon spectrometer (MS) with a magnetic field provided by a system of superconducting toroids.

The results presented in this article use the dataset collected in 2012 by ATLAS from the LHC pp collisions at $\sqrt{s}$ = 8 TeV, using a single-lepton (electron or muon) trigger [33] with a p_{T} threshold of 24 GeV, or a single large-radius jet trigger with a p_{T} threshold of 360 GeV. The integrated luminosity of this dataset after requiring data quality criteria to ensure that all detector components have been operational during data taking is 20.3 fb^{-1}. The uncertainty on the integrated luminosity is ±2.8%. It is derived following the methodology detailed in Ref. [34].

3 Signal and background samples

The acceptance and the reconstructed mass spectra for narrow resonances are estimated with signal samples generated with resonance masses between 200 and 2500 GeV, in 100 GeV steps. The bulk G^* signal events are produced by CalcHEP 3.4 [35] with $k/\bar{M}_{\mathrm{Pl}} = 1.0$, and the W' signal samples are generated with Pythia8.170 [36], setting the coupling scale factor $c = 1$. The factorization and renormalization scales are set to the generated resonance mass. The hadronization and fragmentation are modelled with Pythia8 in both cases, and the CTEQ6L1 [37] (MSTW2008LO [38]) parton distribution functions (PDFs) are used for the G^* (W') signal. The leading-order cross sections and branching ratios for the W' and bulk G^* signal samples for selected mass points and assumed values of the coupling parameters are provided in Table 1.

The backgrounds in the different decay channels are modelled with simulated event samples. The W+jets and Z+jets backgrounds are generated using Sherpa 1.4.1 [39] with CT10 PDFs [40]. A separate sample

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$, and the distance in (ϕ,η) space as $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$.

Table 1: Leading-order cross sections, widths, and branching ratios for the W' boson in the EGM with scale factor $c = 1$ and for the G^* in the bulk RS model with $k/M_{\rm Pl} = 1$ in pp collisions at $\sqrt{s} = 8$ TeV for a variety of mass points.

m [TeV]	$\Gamma_{W'}$ [GeV]	$\sigma(W')$ [fb]	BR($W' \to WZ$) [%]	$\Gamma_{G_{\rm RS}}$ [GeV]	$\sigma(G^*)$ [fb]	BR($G^* \to WW$) [%]	BR($G^* \to ZZ$) [%]
0.5	18.0	2.00×10^5	1.6	18.4	3.11×10^3	34	18
1.0	36.0	1.17×10^4	1.3	55.4	5.60×10^1	19	10
1.5	54.0	1.44×10^3	1.3	89.5	3.14×10^0	17	8
2.0	73.3	2.42×10^2	1.2	122.5	2.90×10^{-1}	16	8
2.5	90.7	5.31×10^1	1.2	155.0	3.20×10^{-2}	16	8

is generated using Alpgen 2.14 [41] to estimate systematic effects, using CTEQ6L1 PDFs and Pythia 6 [36] for fragmentation and hadronization.

The W+jets and Z+jets production cross sections are scaled to next-to-next-to-leading-order (NNLO) calculations [42]. The top quark pair, s-channel single-top quark and Wt processes are modelled by the MC@NLO 4.03 generator [43, 44] with CT10 PDFs, interfaced to Herwig [45] for fragmentation and hadronization and Jimmy [46] for modelling of the underlying event. The top quark pair sample is scaled to the production cross section calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with Top++2.0 [47–52]. The t-channel single-top events are generated by AcerMC [53] with CTEQ6L1 PDFs and Pythia 6 for hadronization. The diboson events are produced with the Herwig generator and CTEQ6L1 PDFs, except for the $\ell\nu\ell'\ell'$ channel which uses POWHEG [54, 55] interfaced to Pythia 6. The diboson production cross sections are normalized to next-to-leading-order predictions [56]. Additional diboson samples for the $\ell\nu q\bar{q}$ channel are produced with the Sherpa generator. QCD multijet samples are simulated with Pythia 6, Herwig, and POWHEG interfaced to Pythia 6.

Generated events are processed with the ATLAS detector simulation program [57] based on the GEANT4 package [58]. Signal and background samples simulated or interfaced with Pythia use an ATLAS specific tune of Pythia [59]. Effects from additional inelastic pp interactions (pile-up) occurring in the same and neighbouring bunch crossings are taken into account by overlaying minimum-bias events simulated by Pythia 8.

4 Object reconstruction and selection

The search channels included in the combination presented in this article use reconstructed electrons, muons, jets and the measurement of the missing transverse momentum.

Electron candidates are selected from energy clusters in the electromagnetic calorimeter within $|\eta| < 2.47$, excluding the transition region between the barrel and the endcap calorimeters ($1.37 < |\eta| < 1.52$), that match a track reconstructed in the ID. Electrons satisfying ‘tight’ identification criteria are used to reconstruct $W \to e\nu$ candidates, while $Z \to ee$ are reconstructed from electrons that satisfy ‘medium’ identification criteria. These criteria are described in Ref. [60]. Muon candidates are reconstructed within the range $|\eta| < 2.5$ by combining tracks with compatible momentum in the ID and the MS [61]. Only leptons with $p_{\rm T} > 25$ GeV are considered.

Backgrounds due to misidentified leptons and non-prompt leptons are suppressed by requiring leptons to be isolated from other activity in the event and also to be consistent with originating from the primary vertex of the event.[2] Upper bounds on calorimeter and track isolation discriminants are used to ensure that the leptons are isolated.

Details of the lepton isolation criteria are given in the publications for the $\ell\nu\ell'\ell'$ [19], $\ell\ell q\bar{q}$ [21], and $\ell\nu q\bar{q}$ [22] channels.

Jets are formed by combining topological clusters reconstructed in the calorimeter system [62], which are calibrated in energy with the local calibration weighting scheme [63] and are considered massless. The measured energies are corrected for losses in passive material, the non-compensating response of the calorimeters and pile-up [64]

Hadronically decaying vector bosons with low p_{T} ($\lesssim 450$ GeV) are reconstructed using a pair of jets. The jets are formed with the anti-k_t algorithm [65] with a radius parameter $R = 0.4$. These jets are hereafter referred to as small-R jets. Only small-R jets with $|\eta| < 2.8$ (2.1) and $p_{\mathrm{T}} > 30$ GeV are considered for the $\ell\nu q\bar{q}$ ($\ell\ell q\bar{q}$) channel. For small-R jets with $p_{\mathrm{T}} < 50$ GeV it is required that the summed scalar p_{T} of the tracks matched to the primary vertex accounts for at least 50% of the scalar summed p_{T} of all tracks matched to the jet. Jets containing hadrons from b-quarks are identified using a multivariate b-tagging algorithm as described in Ref. [66].

Hadronically decaying vector bosons with high p_{T} ($\gtrsim 400$ GeV) can be reconstructed as a single jet with a large radius parameter, or large-R jet, due to the collimated nature of their decay products. These large-R jets, hereafter denoted by J, are first formed with the Cambridge–Aachen (C/A) algorithm [67, 68] with a radius parameter $R = 1.2$. After the jet formation a set of criteria is applied to identify the jet as originating from a hadronically decaying boson (boson tagging). A grooming algorithm is applied to the jets to reduce the effect of pile-up and underlying event activity and to identify a pair of subjets associated with the quarks emerging from the vector boson decay. The grooming algorithm, a variant of the mass-drop filtering technique [69], is described in detail in Ref. [23]. The grooming procedure provides a small degree of discriminating power between jets from hadronically decaying bosons and those originating from background processes.

Jet discrimination is further improved by imposing additional requirements on the large-R jet properties. First, in all of the channels using large-R jets, a requirement on the subjet momentum-balance found at the stopping point of the grooming algorithm, $\sqrt{y} > 0.45$, [3] is applied to the jet. Second, jets are required to have the groomed jet mass within a selection window. Due to the different backgrounds affecting each of the search channels, different mass windows are used for each channel. In the single lepton and dilepton channels, mass windows of $65 < m_J < 105$ GeV and $70 < m_J < 110$ GeV, where m_J represents the jet mass, are used for selecting W and Z bosons. In the fully hadronic channel, mass windows of $69.4 < m_J < 95.4$ GeV and $79.8 < m_J < 105.8$ GeV, which are ± 13 GeV around the expected W or Z reconstructed mass peak, are used for selecting W or Z boson candidates respectively.

The high-p_{T} jets in background events are expected to have a larger charged-particle track multiplicity than the jets emerging from boson decays. This is due to the higher energy scale involved in the fragmentation process of background jets and also due to the larger color charge of gluons in comparison to

[2] The primary vertex of the event is defined as the reconstructed primary vertex with highest $\sum p_{\mathrm{T}}^2$ where the sum is over the tracks associated with this vertex.

[3] $\sqrt{y} \equiv \min(p_{\mathrm{T}j_1}, p_{\mathrm{T}j_2})\frac{\Delta R_{(j_1,j_2)}}{m_0}$, where m_0 is the mass of the groomed jet at the stopping point of the splitting stage of the grooming algorithm, $p_{\mathrm{T}j_1}$ and $p_{\mathrm{T}j_2}$ are the transverse momenta of the subjets at the stopping point of the splitting stage of the grooming algorithm and $\Delta R_{(j_1,j_2)}$ is the distance in (ϕ, η) space between these subjets.

quarks. Hence, to improve the sensitivity of the search in the fully hadronic channel, a requirement on the charged-particle track multiplicity matched to the large-R jet prior to the grooming, $n_{\mathrm{trk}} < 30$, is used to discriminate between jets originating from boson decays and jets from background processes. Charged-particle tracks reconstructed with the ID and consistent with particles originating from the primary vertex and with $p_{\mathrm{T}} \geq 500$ MeV are matched to a large-R jet by representing each track by a "ghost" constituent that is collinear with the track at the perigee with negligible energy during jet formation [70].

The missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated from the negative vector sum of the transverse momenta of all reconstructed objects, including electrons, muons, photons and jets, as well as calibrated energy deposits in the calorimeter that are not associated to these objects, as described in Ref. [71].

5 Analysis channels

The selections in the four analysis channels $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ are mutually exclusive and therefore the channels are statistically independent. This independence is enforced by the required lepton multiplicity of the events at a pre-selection stage, with lepton selection criteria looser than those finally applied in the individual channels. The searches in the individual channels are described in detail in their corresponding publications [19, 21–23]. Table 2 summarises the dominant backgrounds affecting each of the individual channels and the methods used to estimate these backgrounds. Summaries of the event selection and classification criteria are given in Tables 3 and 4.

Table 2: Dominant background to the individual channels and their estimation methods.

Channel	Dominant background	Estimation method
$\ell\nu\ell'\ell'$	WZ production	MC (POWHEG)
$\ell\ell q\bar{q}$	Z+jets	MC (Sherpa), normalisation and shape correction data driven
$\ell\nu q\bar{q}$	W/Z+jets	MC (Sherpa), normalisation and shape correction data driven
JJ	QCD jets	data driven

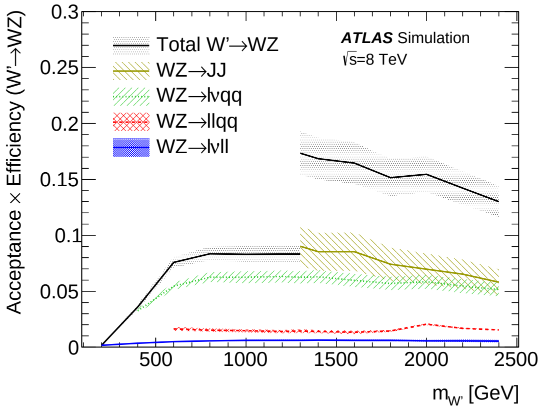
The $\ell\nu\ell'\ell'$ analysis channel is described in detail in Ref. [19]. For the purpose of combination the binning of the diboson candidates' invariant mass distribution is adjusted. The $\ell\nu\ell'\ell'$ channel requires exactly three leptons with $p_{\mathrm{T}} > 25$ GeV, of which at least one must be geometrically matched to a lepton reconstructed by a trigger algorithm. Events with additional leptons with $p_{\mathrm{T}} > 20$ GeV are vetoed. At least one pair of oppositely-charged, same-flavour leptons is required to have an invariant mass within the Z mass window $|m_{\ell\ell} - m_Z| < 20$ GeV. If there are two acceptable combinations satisfying this requirement the combination with the mass value closer to the Z boson mass is chosen as the Z candidate. The event is required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV. The W candidate is reconstructed from the third lepton, assuming the neutrino is the only source of $E_{\mathrm{T}}^{\mathrm{miss}}$ and constraining the $(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}})$ system to have the pole mass of the W. This constraint results in a quadratic equation with two solutions for the longitudinal momentum of the neutrino. If the solutions are real, the one with the smaller absolute value is used. If the solutions are complex, the real part is used. To enhance the signal sensitivity, the rapidity difference must satisfy $\Delta y(W, Z) < 1.5$ and requirements are placed on the azimuthal angle difference $\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}})$. Exclusive *high-mass* and *low-mass* regions are defined with $\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) < 1.5$ for boosted W bosons and $\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) > 1.5$ for W bosons at low p_{T}, respectively. The main background sources in the $\ell\nu\ell'\ell'$ channel are SM WZ and ZZ processes with leptonic decays of the W and Z bosons, and are estimated from simulation. Other background sources are W/Z+jets, top quark and multijet production, where one or several jets are mis-reconstructed as leptons. To estimate these backgrounds the mis-reconstruction rate of jets as leptons is determined with data-driven methods, and applied to control data samples with leptons and one or more jets.

The $\ell\ell q\bar{q}$ analysis channel is described in detail in Ref. [21]. The $\ell\ell q\bar{q}$ channel requires exactly two leptons, having the same flavour and with $p_{\mathrm{T}} > 25$ GeV. Muon pairs are required to have opposite charge. At least one lepton is required to be matched to a lepton reconstructed by a trigger algorithm. The invariant mass of the lepton pair must be within 25 GeV of the Z mass. Three regions (*merged*, *high-p_{T} resolved* and *low-p_{T} resolved*) are defined to optimize the selection for different mass ranges. The merged region requirements are $p_{\mathrm{T}}(\ell\ell) > 400$ GeV and a groomed large-R jet described in Section 4 with $p_{\mathrm{T}}(J) > 400$ GeV and satisfying the boson-tagging criteria. The high-p_{T} resolved region is defined by $p_{\mathrm{T}}(\ell\ell) > 250$ GeV, $p_{\mathrm{T}}(jj) > 250$ GeV, and the low-p_{T} resolved region requires $p_{\mathrm{T}}(\ell\ell) > 100$ GeV, $p_{\mathrm{T}}(jj) > 100$ GeV. The invariant mass requirement on the jet system is 70 GeV $< m_{jj/J} <$ 110 GeV. The three regions are made exclusive by applying the above selections in sequence, starting with the merged region, and progressing with the high-p_{T} and then the low-p_{T} resolved regions. The main background sources in the $\ell\ell q\bar{q}$ channel are Z+jets, followed by top-quark pair and non-resonant vector-boson pair production. Background estimates are based on simulation. Additionally, for the main background source, Z+jets, the shape of the invariant mass distribution is modelled with simulation, while the normalization and a linear shape correction are determined from data in a control region, defined as the side-bands of the $q\bar{q}$ invariant mass distribution outside the signal region.

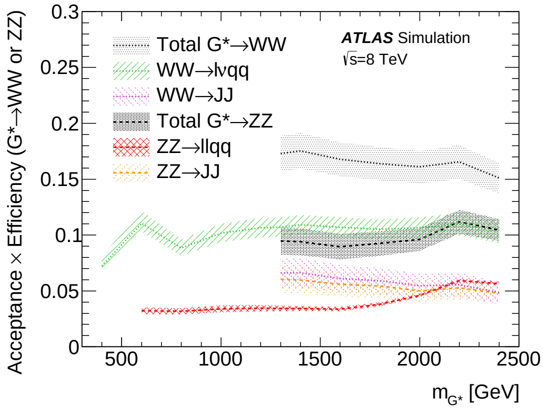
The $\ell\nu q\bar{q}$ analysis channel is described in detail in Ref. [22]. In the $\ell\nu q\bar{q}$ channel exactly one lepton with $p_{\mathrm{T}} > 25$ GeV and matched to a lepton reconstructed by the trigger is required. The missing transverse momentum in the event is required to be $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. Similar to the $\ell\ell q\bar{q}$ channel the event selection contains three different mass regions of the signal, referred to as *merged*, *high-p_{T} resolved* and *low-p_{T} resolved* regions. In the merged region where the hadronic decay products merge into a single jet, a groomed large-R jet with $p_{\mathrm{T}} > 400$ GeV and 65 GeV $< m_J <$ 105 GeV is required. The leptonically decaying W candidate is reconstructed using the same W mass constraint technique used in the $\ell\nu\ell'\ell'$ channel. The leptonically decaying $W \to \ell\nu$ must have $p_{\mathrm{T}}(\ell\nu) > 400$ GeV, where $p_{\mathrm{T}}(\ell\nu)$ is reconstructed from the sum of the charged-lepton momentum vector and the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector. To suppress the background from top-quark production, events with an identified b-jet separated by $\Delta R > 0.8$ from the large-R jet are rejected. Additionally, in the electron channel the leading large-R jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ are required to be separated by $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, J) > 1$ to reject multi-jet background. If the event does not satisfy the criteria of the merged region, the resolved region selection criteria are applied. In the high-p_{T} resolved region, two small-R jets with $p_{\mathrm{T}} > 80$ GeV are required to form the hadronically decaying W/Z candidate with a transverse momentum of $p_{\mathrm{T}}(jj) > 300$ GeV and an invariant mass of 65 GeV $< m_{jj} <$ 105 GeV. The leptonically decaying $W \to \ell\nu$ must have $p_{\mathrm{T}}(\ell\nu) > 300$ GeV. The event is rejected if a b-jet is identified in addition to the two leading jets. In the electron channel the leading small-R jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ are required to be separated by $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j) > 1$. If the event does not pass the selection requirements of the high-p_{T} resolved region the selection of the low-p_{T} resolved region is used, where $p_{\mathrm{T}}(jj) > 100$ GeV and $p_{\mathrm{T}}(\ell\nu) > 100$ GeV are applied. The dominant background in the $\ell\nu q\bar{q}$ channel is W/Z+jets production, followed by top quark production, and multijet and diboson processes. The shape of the invariant mass distribution for the W/Z+jets background is modelled by simulation, while the normalization is determined from data in a control region, defined as the side-bands of the $q\bar{q}$ invariant mass distribution outside the signal region. The $p_{\mathrm{T}}(W)$ distribution of the W+jets simulation is corrected using data to improve the modelling. The sub-dominant background processes are estimated using simulation only (diboson), or simulation and data-driven techniques (multijet, top quark).

The JJ analysis channel is described in detail in Ref. [23]. For the combined G^* search the analysis is extended, combining the WW and ZZ selections into a single inclusive analysis of both decay modes. The analysis of the fully hadronic decay mode selects events that pass a large-R jet trigger[4] with a nominal threshold of 360 GeV in transverse momentum and have at least two large-R jets within $|\eta| < 2.0$, a rapidity difference between the two jets of $|\Delta y_{12}| < 1.2$, and an invariant mass of the two jets of $m(JJ) >$ 1.05 TeV. Events that contain one or more leptons with $p_{\mathrm{T}} > 20$ GeV or missing transverse momentum in excess of 350 GeV are vetoed. The large-R jets must satisfy the boson-tagging criteria described in Section 4. Furthermore, the dijet p_{T} asymmetry defined as $A = (p_{\mathrm{T}1} - p_{\mathrm{T}2})/(p_{\mathrm{T}1} + p_{\mathrm{T}2})$ must be less then 0.15 to avoid mis-measured jets. In the search for the EGM W' decaying to WZ, events are selected by requiring one W boson candidate and one Z boson candidate in each event by applying the selections described in Section 4. In the search for the bulk G^* decaying to WW and ZZ, events are selected by requiring two W boson or two Z boson candidates by applying the selections described in Section 4. Due to the overlapping jet mass windows applied to select W and Z candidates, the selection for the EGM W' and the bulk G^* are not exclusive and about 20% of the inclusive event sample is shared. In the fully hadronic channel the dominant background is dijet production. The dijet background is estimated by a parametric fit with a smoothly falling function to the observed dijet mass spectrum in the data. Only diboson resonances with mass values > 1.3 TeV are considered as signal for this analysis channel.

The selections described above have a combined acceptance times efficiency of up to 17% for $G^* \to WW$, up to 11% for $G^* \to ZZ$, and up to 17% for $W' \to WZ$. The acceptance times efficiency includes the W and Z branching ratios. Figs. 1(a) and 1(b) summarize the acceptance times efficiency for the different analyses as a function of the W' mass and of the G^* mass, considering only decays of the resonance into VV, where V denotes a W or a Z boson.



(a)



(b)

Figure 1: Signal acceptance times efficiency for the different analyses entering the combination for (a) the EGM W' model and (b) for the bulk G^* model. The branching ratio of the new resonance to dibosons is included in the denominator. The error bands represent the combined statistical and systematic uncertainties.

[4] The trigger uses anti-k_t jets with $R = 1.0$.

Table 3: Summary of the event selection requirements in the different search channels. The selected events are further classified into different kinematic categories as listed in Table 4.

Channel	Leptons	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	Boson identification
$\ell\nu\ell'\ell'$	3 leptons $p_{\mathrm{T}} > 25$ GeV	–	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 20$ GeV
$\ell\ell q\bar{q}$	2 leptons $p_{\mathrm{T}} > 25$ GeV	2 small-R jets or 1 large-R jet $p_{\mathrm{T}} > 30$ GeV	–	$\lvert m_{\ell\ell} - m_Z\rvert < 25$ GeV 70 GeV $< m_{jj} <$ 110 GeV 70 GeV $< m_J <$ 110 GeV , $\sqrt{y} > 0.45$
$\ell\nu q\bar{q}$	1 lepton $p_{\mathrm{T}} > 25$ GeV	2 small-R jets or 1 large-R jet $p_{\mathrm{T}} > 30$ GeV No b-jet with $\Delta R(b, W/Z) > 0.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	65 GeV $< m_{jj} <$ 105 GeV 65 GeV $< m_J <$ 105 GeV, $\sqrt{y} > 0.45$
JJ	lepton veto	2 large-R jets, $\lvert\eta\rvert < 2.0$, $p_{\mathrm{T}} > 540$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} < 350$ GeV	$\lvert m_{W/Z} - m_J\rvert < 13$ GeV $\sqrt{y} > 0.45$, $n_{\mathrm{trk}} < 30$

Table 4: Summary of the event classification requirements in the different search channels. The classifications are mutually exclusive, applying the requirements in sequence beginning with the high-p_{T} merged, followed by the high-p_{T} resolved and finally with the low-p_{T} resolved classification.

<table>
<tr><th>Channel</th><th>High-p_{T} merged</th><th>High-p_{T} resolved (high mass)</th><th>Low-p_{T} resolved (low mass)</th></tr>
<tr><td rowspan="2">$\ell\nu\ell'\ell'$</td><td rowspan="2">–</td><td colspan="2">$\Delta y(W, Z) < 1.5$</td></tr>
<tr><td>$\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) < 1.5$</td><td>$\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) > 1.5$</td></tr>
<tr><td>$\ell\ell q\bar{q}$</td><td>$p_{\mathrm{T}}(\ell\ell) > 400$ GeV
$p_{\mathrm{T}}(J) > 400$ GeV</td><td>$p_{\mathrm{T}}(\ell\ell) > 250$ GeV
$p_{\mathrm{T}}(jj) > 250$ GeV</td><td>$p_{\mathrm{T}}(\ell\ell) > 100$ GeV
$p_{\mathrm{T}}(jj) > 100$ GeV</td></tr>
<tr><td rowspan="3">$\ell\nu q\bar{q}$</td><td rowspan="2">1 large-R jet, $p_{\mathrm{T}} > 400$ GeV
$p_{\mathrm{T}}(\ell\nu) > 400$ GeV</td><td>2 small-R jets, $p_{\mathrm{T}} > 80$ GeV</td><td>2 small-R jets, $p_{\mathrm{T}} > 30$ GeV</td></tr>
<tr><td>$p_{\mathrm{T}}(jj) > 300$ GeV
$p_{\mathrm{T}}(\ell\nu) > 300$ GeV</td><td>$p_{\mathrm{T}}(jj) > 100$ GeV
$p_{\mathrm{T}}(\ell\nu) > 100$ GeV</td></tr>
<tr><td colspan="3">$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j) > 1$ (electron channel)</td></tr>
<tr><td>JJ</td><td>$\lvert\Delta y_{12}\rvert < 1.2$
$m(JJ) > 1.05$ TeV</td><td colspan="2">–</td></tr>
</table>

6 Statistical procedure

The combination of the individual channels proceeds with a simultaneous analysis of the invariant mass distributions of the diboson candidates in the different channels. For each hypothesis being tested, only the channels sensitive to that hypothesis are included in the combination. The signal strength, μ, defined as a scale factor on the cross section times branching ratio predicted by the signal hypothesis, is the parameter of interest. The analysis follows the Frequentist approach with a test statistic based on the profile-likelihood ratio [72]. The test statistic extracts information on the signal strength from a binned maximum-likelihood fit of the signal-plus-background model to the data. The effect of a systematic uncertainty k on the likelihood is modelled with a nuisance parameter, θ_k, constrained with a corresponding probability density function $f(\theta_k)$, as explained in the publications corresponding to the individual channels [19, 21–23]. In this manner, correlated effects across the different channels are modelled by the use of a common nuisance parameter and its corresponding probability density function. The likelihood model, $\mathcal{L}$, is given by:

$$\mathcal{L} = \prod_c \prod_i \mathrm{Pois}\left(n^{\mathrm{obs}}_{i_c} \middle| n^{\mathrm{sig}}_{i_c}(\mu, \theta_k) + n^{\mathrm{bkg}}_{i_c}(\theta_k)\right) \prod_k f_k(\theta_k) \tag{1}$$

where the index c represents the analysis channel, and i represents the bin in the invariant mass distribution, n^{obs}, the observed number of events, n^{sig} the number of expected signal events, and n^{bkg} the expected number of background events.

The compatibility between the observations of different channels with a common signal strength of a particular resonance model and mass is quantified using a profile-likelihood-ratio test. The corresponding profile-likelihood ratio is

$$\lambda(\mu) = \frac{\mathcal{L}\left(\mu, \hat{\hat{\theta}}(\mu)\right)}{\mathcal{L}\left(\hat{\mu}_A, \hat{\mu}_B, \hat{\theta}\right)}, \tag{2}$$

where μ is the common signal strength, $\hat{\mu}_A$ and $\hat{\mu}_B$ are the unconditional maximum likelihood (ML) estimators of the independent signal strengths in the channels being compared, $\hat{\theta}$ are the unconditional ML estimators for the nuisance parameters, and $\hat{\hat{\theta}}(\mu)$ are the conditional ML estimators of θ for a given value of μ. The compatibility between the observations is tested by the probability of observing $\lambda(\hat{\mu})$, where $\hat{\mu}$ is the ML estimator for the common signal strength for the model in question. If the two channels being compared have a common signal strength, i.e. $\mu = \mu_A = \mu_B$, then in the asymptotic limit $-2\log(\lambda(\hat{\mu}))$ is expected to be χ^2 distributed with one degree of freedom.

The significance of observed excesses over the background-only prediction is quantified using the local p-value (p_0), defined as the probability of the background-only model to produce a signal-like fluctuation at least as large as observed in the data. Upper limits on μ for W' in the EGM and G^* in the bulk RS model at the simulated resonance masses are evaluated at the 95% CL following the CL_s prescription [73]. Lower mass limits at the 95% CL for new diboson resonances in these models are obtained by finding the maximum resonance mass where the 95% CL upper limit on μ is less or equal to 1. This mass is found by interpolating between the limits on μ at the simulated signal masses. The interpolation assumes monotonic and smooth behaviour of the efficiencies for the signal and background processes, and that the impact of the variation of signal mass distributions between adjacent test masses is negligible.

In the combined analysis to search for W' resonances, all four individual channels are used. For the charge-neutral bulk G^*, only the $\ell\nu qq$, $\ell\ell qq$, and the JJ channels contribute to the combination, and in the case of the fully hadronic channel, a merged signal region resulting from the union of the WW and ZZ signal regions is used in the analysis. The background to this merged signal region is estimated using the same technique as for the individual signal regions. Table 5 summarises the channels and signal regions combined in the analysis for the EGM W' and bulk G^*.

Table 5: Channels and signal regions contributing to the combination for the EGM W' and bulk G^*.

Channel	Signal region	W' mass range [TeV]	G^* mass range [TeV]
$\ell\nu\ell'\ell'$	low-mass	0.2–1.9	–
	high-mass	0.2–2.5	–
$\ell\ell q\bar{q}$	low-p_{T} resolved	0.3–0.9	0.2–0.9
	high-p_{T} resolved	0.6–2.5	0.6–0.9
	merged	0.9–2.5	0.9–2.5
$\ell\nu q\bar{q}$	low-p_{T} resolved	0.3–0.8	0.2–0.7
	high-p_{T} resolved	0.6–1.1	0.6–0.9
	merged	0.8–2.5	0.8–2.5
JJ	WZ selection	1.3–2.5	–
	WW+ZZ selection	–	1.3–2.5

7 Systematic uncertainties

The sources of systematic uncertainty along with their effects on the expected signal and background yields for each of the individual channels used in this combination are described in detail in their corresponding publications [19, 21–23]. Although the results from the different search channels in this combination are statistically independent, commonalities between the different search channels, such as the objects used, the signal and background simulation, and the integrated luminosity estimation, introduce correlated effects in the signal and background expectations. Whenever an effect due to an uncertainty in the triggering, identification, or reconstruction of leptons is considered for a channel, it is treated as fully correlated with the effects due to this uncertainty in other channels.

In the same manner, the effects of each uncertainty related to the small-R jet energy scale and resolution are treated as fully correlated in all channels using small-R jets or $E_{\mathrm{T}}^{\mathrm{miss}}$. For the search channels using large-R jets, uncertainties in the large-R jet energy scale, energy resolution, mass scale, mass resolution, or in the modelling of the boson-tagging discriminant $\sqrt{y}$ are taken as fully correlated. Uncertainties in the data-driven background estimates are treated as uncorrelated. The effects of uncertainty in the initial- and final-state radiation (ISR and FSR) modelling and in the PDFs are each treated as fully correlated across all search channels.

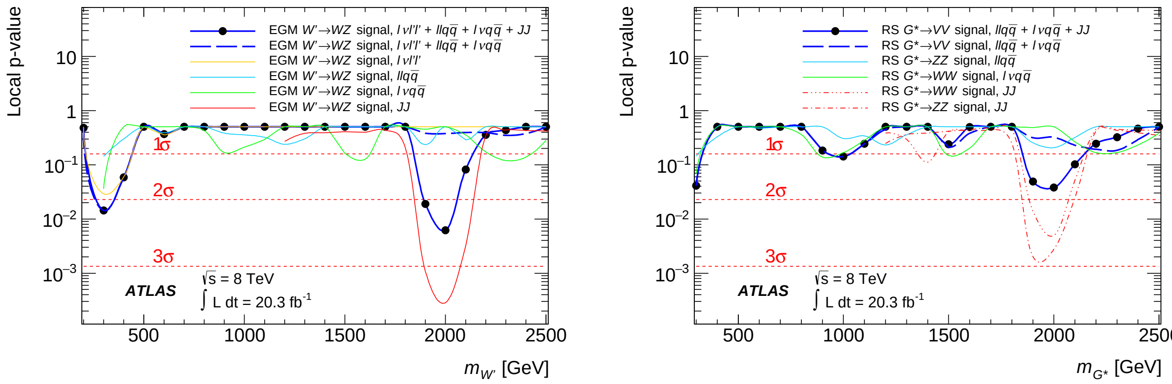
The effect of a single source of systematic uncertainty on the combined limit can be ranked by the loss in sensitivity caused by its inclusion. To quantify the loss of sensitivity at a given mass point the value computed with all systematic uncertainties included is compared to the value obtained excluding the single systematic uncertainty. In the low mass region at $\lesssim 0.5$ TeV the leading uncertainty is the modelling of the

SM diboson background in the dominant $\ell\nu\ell'\ell'$ channel with an impact of 35% sensitivity degradation in the combined limit for EGM W'. The leading source of uncertainty in case of the G^* limit is the modelling of the Z+jets background in the $\ell\nu q\bar{q}$channel with a degradation of 25%. In the intermediate mass region up to $\lesssim$ 1.5 TeV the uncertainty on the normalisation of the W+jets background in the $\ell\nu q\bar{q}$ channel is dominating with 20% to 30% degradation of the EGM W' limit and 25% to 55% degradation of the G^* limit depending on the mass point, while in the high mass region up to 2 TeV the shape uncertainty on the W+jets background dominates with a degradation of around 25% for the EGM W' limit and 35% for the G^* limit.

8 Results

Figure 2 shows the p_0-value obtained in the search for the EGM W' and G^* as a function of the resonance mass for the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels combined and for the individual channels. For the full combination the largest deviation from the background-only expectation is found in the EGM W' search at around 2.0 TeV with a p_0-value corresponding to 2.5 standard deviations (σ). This is smaller than the p_0-value of 3.4 σ observed in the JJ channel alone because the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, and $\ell\nu q\bar{q}$ channels are more consistent with the background-only hypothesis.

The compatibility of the individual channels is quantified with the test described in Section 6. In the mass region around 2 TeV the JJ channel presents an excess while the other channels are in good agreement with the background-only expectation. For the EGM W' benchmark the compatibility of the combined $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, and $\ell\nu q\bar{q}$ channels with the JJ channel is at the level of 2.9 σ. When accounting for the probability for any of the four channels to fluctuate the compatibility is found to be at the level of 2.6 σ. In comparison the corresponding test for the bulk G^* interpretation shows better compatibility.

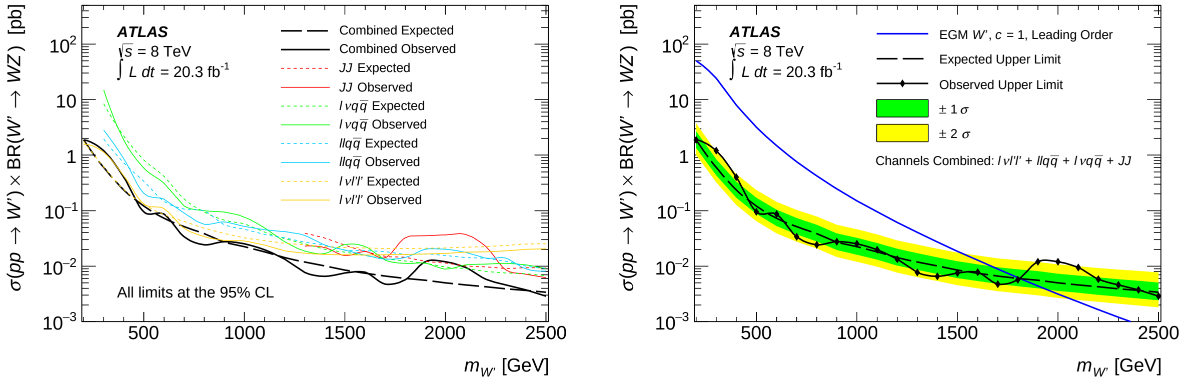


(a)

(b)

Figure 2: The p_0-value for the individual and combined channels for (a) the EGM W' search in the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels and (b) the bulk G^* search in the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels.

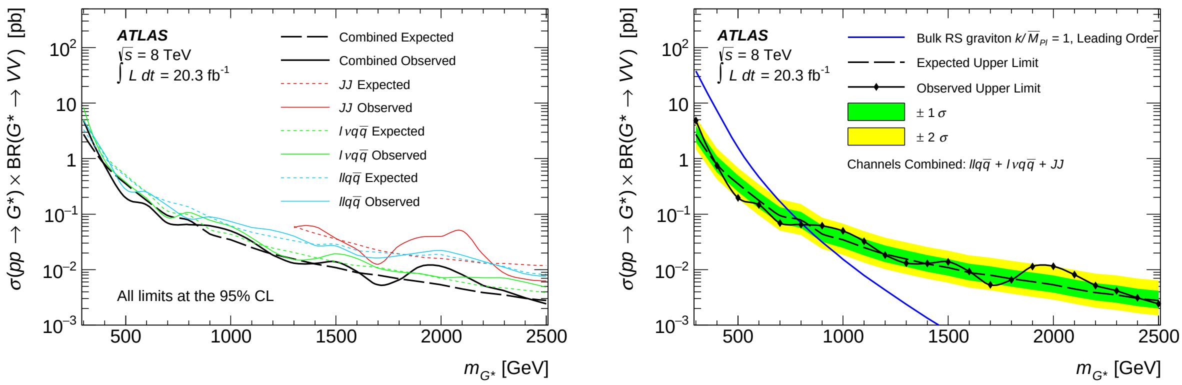
Figure 3 shows the combined upper limit on the EGM W' production cross section times its branching ratio to WZ at the 95% CL in the mass range from 300 GeV to 2.5 TeV. In Fig. 3(a) the observed and expected limits of the individual and combined channels are shown. In Fig. 3(b) the observed and expected combined limits are compared with the theoretical EGM W' prediction. The resulting combined lower limit on the EGM W' mass using a LO cross-section calculation is observed to be 1.81 TeV, with an expected limit of 1.81 TeV. The most stringent observed mass limit from an individual channel is 1.59 TeV at NNLO in the $\ell\nu q\bar{q}$ analysis.



(a) (b)

Figure 3: The 95% CL limits on (a) the EGM W' using the $\ell\nu\ell'\ell'$, $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels and their combination, and (b) the combined 95% CL limit with the green (yellow) bands representing the $1\,\sigma$ $(2\,\sigma)$ intervals of the expected limit including statistical and systematic uncertainties.

In Fig. 4 the observed and expected upper limits at the 95% CL on the bulk G^* production cross section times its branching ratio to WW and ZZ are shown in the mass range from 200 GeV to 2.5 TeV. In Fig. 4(b) the observed and expected limits of the individual and combined channels are shown and compared with the theoretical bulk G^* prediction for $k/\overline{M}_{\rm Pl} = 1$. The combined, lower mass limit for the bulk G^*, assuming $k/\overline{M}_{\rm Pl} = 1$, is 810 GeV, with an expected limit of 790 GeV. The most stringent lower mass limit from the individual $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$ and JJ channels is 760 GeV from the $\ell\nu q\bar{q}$ channel.



(a) (b)

Figure 4: The 95% CL limits on (a) the bulk G^* using the $\ell\ell q\bar{q}$, $\ell\nu q\bar{q}$, and JJ channels and their combination, and (b) the combined 95% CL limit with the green (yellow) bands representing the $1\,\sigma$ $(2\,\sigma)$ intervals of the expected limit including statistical and systematic uncertainties.

9 Conclusion

A combination of individual searches in all-leptonic, semileptonic, and all-hadronic final states to search for new heavy bosons decaying to WW, WZ and ZZ is presented. The searches use 20.3 fb^{-1} of 8 TeV pp collision data collected by the ATLAS detector at the LHC. Within the combined result, no significant excess over the background-only expectation in the invariant mass distribution of the diboson candidates is observed. Upper limits on the production cross section times branching ratio to dibosons at the 95% CL are evaluated within the context of an extended gauge model with a heavy W' boson and a bulk Randall–Sundrum model with a heavy spin-2 graviton. The combination significantly improves both the cross-section limits and the mass limits for EGM W' and bulk G^* production over the most stringent limits of the individual analyses. The observed lower limit on the EGM W' mass is found to be 1.81 TeV and for the bulk G^* mass, assuming $k/\overline{M}_{\mathrm{Pl}} = 1$, the observed limit is 810 GeV.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Region Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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