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Search for WZ resonances in the fully leptonic channel using pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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ABSTRACT

A search for resonant WZ production in the $\ell\nu\ell'\ell'$ ($\ell, \ell' = e, \mu$) decay channel using 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data collected by the ATLAS experiment at LHC is presented. No significant deviation from the Standard Model prediction is observed and upper limits on the production cross sections of WZ resonances from an extended gauge model W' and from a simplified model of heavy vector triplets are derived. A corresponding observed (expected) lower mass limit of 1.52 (1.49) TeV is derived for the W' at the 95% confidence level.

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1. Introduction

The search for diboson resonances is an essential complement to the investigation of the source of electroweak symmetry breaking. Despite the compatibility between the properties of the newly discovered particle at the LHC [1–4] with those expected for the Standard Model (SM) Higgs boson, the naturalness problem associated with a light Higgs boson suggests that the SM is likely to be an effective theory valid only at low energies. Extensions of the SM, such as Grand Unified Theories [5], Little Higgs models [6], Technicolor [7–10], more generic Composite Higgs models [11,12], or models of extra dimensions [13–15], predict diboson resonances at high masses.

This Letter presents a search for resonant WZ production in the fully leptonic decay channels $WZ \to \ell\nu\ell'\ell'$ ($\ell, \ell' = e, \mu$) using 20.3 fb^{-1} of pp collision data collected by the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. Four possible leptonic decay channels ($e\nu ee$, $e\nu\mu\mu$, $\mu\nu ee$ and $\mu\nu\mu\mu$) are considered. To interpret the results, the extended gauge model (EGM) [16] with a spin-1 W' boson is used as a benchmark signal hypothesis. In this model, the couplings of the EGM W' boson to the SM particles are identical to those of the W boson, except for its coupling to WZ, which is suppressed with respect to the SM WWZ triple gauge coupling by a factor of $(m_W/m_{W'})^2$ and entails a linear relationship between the resonance width and mass. The branching ratio BR($W' \to WZ$) varies between 1% and 2% for a W' mass range 200–2000 GeV. In other scenarios, such as for leptophobic W' bosons [17–19], the decay to a pair of gauge bosons can be a dominant channel. A narrow W' resonance is predicted in the EGM, with an intrinsic decay width that is negligible with respect to the experimental resolutions on the reconstructed WZ invariant mass. Possible interferences between signal and SM backgrounds are assumed to be small and are neglected. Under these assumptions, the final results presented here can be reinterpreted in terms of any narrow spin-1 resonance for a given signal efficiency and acceptance.

A phenomenological Lagrangian for heavy vector triplets (HVT) [20] has recently been introduced, where the couplings of the new fields to fermions and gauge bosons are defined in terms of parameters. By scanning these parameters the generic Lagrangian describes a large class of models. The triplet field, which mixes with the SM gauge bosons, couples to the fermionic current through the combination of parameters $g^2 c_F/g_V$ and to the Higgs and vector bosons through $g_V c_H$, where g is the $SU(2)_L$ gauge coupling, the parameter g_V represents the coupling strength to vector bosons, and c_F and c_H allow to modify the couplings and are expected to be close to unity in most specific models. Two benchmark models, provided in Ref. [20], are used here as well. In Model A, weakly coupled vector resonances arise from an extension of the SM gauge group [21]. In Model B, the heavy vector triplet is produced in a strongly coupled scenario, for example in a Composite Higgs model [22]. In Model A, the branching fractions to fermions and gauge bosons are comparable, whereas for Model B, fermionic couplings are suppressed.

Direct searches for WZ resonances have been reported by several experiments. The ATLAS Collaboration reported on searches for a W' resonance using approximately 1 fb^{-1} of data for the $\ell\nu\ell'\ell'$ channel and 4.7 fb^{-1} of data for the $\ell\nu jj$ channel, where j is a hadronic jet, both at $\sqrt{s} = 7$ TeV, and excluded an EGM W' boson with mass below 0.76 TeV [23] and 0.95 TeV [24] respectively. The CMS Collaboration searched for the production of generic WZ resonances in the semileptonic final state, and obtained upper limits on the production cross section as a function of signal mass

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and width [25]. They also analyzed dijet signatures containing jets tagged as W and Z boson decays, and excluded EGM W' bosons with masses below 1.7 TeV [26]. The advantage of the three-lepton WZ final state over its partial or fully hadronic final state counterparts is its better sensitivity at the lower end of the mass spectrum due to its significantly smaller SM backgrounds and superior mass resolution. The CMS Collaboration analyzed 5 fb^{-1} of data at $\sqrt{s} = 7$ TeV in the $\ell\nu\ell'\ell'$ channel, and EGM W' bosons with masses below 1.143 TeV [27] were excluded.

2. The ATLAS detector

The ATLAS detector [28] consists of an inner tracking detector (ID), electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer. The ID is immersed in a 2 T axial magnetic field, generated by a superconducting solenoid, and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID provides a pseudorapidity coverage of $|\eta| < 2.5$.[1]

The EM calorimeters are composed of interspersed lead and liquid argon, acting as absorber and active material respectively, with high granularity in both the barrel ($|\eta| < 1.475$) and end-cap up to the end of the tracker acceptance ($1.375 < |\eta| < 2.5$), and somewhat coarser granularity from $|\eta| = 2.5$ to 3.2. The hadronic calorimeter uses steel and scintillator tiles in the barrel region, while the endcaps use liquid argon as the active material and copper as an absorber. The muon spectrometer (MS) is based on three large superconducting air-core toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters. Three layers of precision tracking chambers, consisting of drift tubes and cathode strip chambers, enable precise muon track measurements in the pseudorapidity range of $|\eta| < 2.7$, and resistive-plate and thin-gap chambers provide muon triggering capability in the range of $|\eta| < 2.4$.

3. Data and Monte Carlo modelling

The data analyzed here were collected by the ATLAS detector at the LHC in pp collisions at $\sqrt{s} = 8$ TeV during the 2012 data-taking run. Events are selected using a combination (logical OR) of isolated and non-isolated single-lepton (e or μ) triggers. The p_T thresholds are 24 GeV for isolated single-lepton triggers and 60 (36) GeV for non-isolated single-e (μ) triggers. The requirement that three high-p_T leptons are in the final state gives a trigger efficiency above 99.5%. After data-quality requirements are applied, the total integrated luminosity is 20.3 fb^{-1} with an uncertainty of 2.8% [29].

The baseline EGM W' signals are generated with PYTHIA 8.162 [30] and the MSTW2008LO [31] parton distribution function (PDF) set. The production cross section times branching fraction (with $W \to e\nu, \mu\nu, \tau\nu$, where all τ decays are considered, and $Z \to ee, \mu\mu$) are scaled to their theoretical predictions at next-to-next-to-leading order (NNLO) using ZWPROD [32], which are 1.43 pb for $m_{W'} = 200$ GeV, 4.12 fb for $m_{W'} = 1$ TeV, and 0.08 fb for $m_{W'} = 2$ TeV. In the $W \to \tau\nu$ component, only the leptonic τ decays enter the signal acceptance, albeit slightly and only at high signal mass, whereas the $Z \to \tau\tau$ component is totally negligible. The intrinsic decay widths of the EGM W' scale linearly with $m_{W'}$ at high mass and are 5.5 GeV for $m_{W'} = 200$ GeV, 36 GeV for $m_{W'} = 1$ TeV, and 72 GeV for $m_{W'} = 2$ TeV. These are significantly less than the experimental resolutions, which have Gaussian widths of the order of 25 GeV for $m_{W'} = 200$ GeV, 100 GeV for $m_{W'} = 1$ TeV, and 180 GeV for $m_{W'} = 2$ TeV. MC samples were produced for the EGM W' signal from 200 GeV to 400 GeV at intervals of 50 GeV and from 400 GeV to 2 TeV at intervals of 200 GeV. An interpolation procedure is adopted to obtain the distributions for mass points between 200 GeV and 400 GeV with 25 GeV step size and from 400 GeV to 2 TeV with 50 GeV step size.

Table 1
Overview of the primary MC samples. The backgrounds from misidentified jets are estimated from the data.

Process	Generator	Parton Shower	PDF
W'	PYTHIA	PYTHIA	MSTW2008LO
WZ	POWHEG-BOX	PYTHIA	
ZZ	POWHEG-BOX	PYTHIA	CT10
$Z\gamma$	SHERPA	SHERPA	
$t\bar{t} + W/Z$	MadGraph	PYTHIA	CTEQ6L1

The dominant SM WZ background is modelled by POWHEG-BOX [33–36], a next-to-leading-order (NLO) event generator combined with the NLO CT10 PDF set [37]. Background events arising from ZZ are modelled with POWHEG-BOX, while those from $t\bar{t} + W/Z$ processes are generated with MadGraph 5.1.4.8 [38] together with the CTEQ6L1 [39] PDF set. All these events are interfaced with PYTHIA, using the AU2 tune [40] for parton showering.

A second category of background arises from photons misidentified as electrons, mainly from $Z\gamma$ production. A photon can be misreconstructed as an electron if it lies close to a charged particle track or if the photon converts to e^+e^- after interacting with the material in front of the calorimeter. This contribution is estimated using simulated $Z\gamma$ MC events generated with SHERPA 1.4.0 [41].

Finally, a third category of background includes all other sources where one or more jets are misidentified as an isolated lepton. The contributions from these *fake* backgrounds are estimated using a data-driven method as described in Section 6. The contribution from events with only one jet misidentified as an isolated lepton is found to be dominant while those with more than one are found to be negligible. Thus, in this analysis the *fake* backgrounds are denoted by $\ell\ell' + \text{jets}$.

An overview of the major MC samples used is presented in Table 1.

Monte Carlo (MC) events are processed through the full detector simulation [42] using GEANT4 [43], and their reconstruction is performed with the same software used to reconstruct data events. Correction factors for lepton reconstruction and identification efficiencies are applied to the simulation to account for differences with respect to data. The simulated lepton four-momenta are tuned, via calorimeter energy scaling and momentum resolution smearing, to reproduce the distributions observed in data from leptonic W, Z and J/ψ decays after calibration. Furthermore, additional inelastic pp collision events are overlaid with the hard scattering process in the MC simulation and then reweighted to reproduce the observed average number of interactions per bunch-crossing in data.

4. Object reconstruction

Electron candidates are reconstructed in the region of the EM calorimeter with $|\eta| < 2.47$ by matching the calorimeter clusters to the tracks in the ID. The transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) is excluded. Candidate electrons must satisfy the medium quality definition [44]

[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 $\eta = -\ln\tan(\theta/2)$. The separation between final-state particles is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The transverse momentum is denoted by p_T.

re-optimized for 2012 data-taking conditions, which is based on a set of requirements on the calorimeter shower shape, track quality, and track matching with the calorimeter cluster. The longitudinal impact parameter z_0 of the associated track with respect to the primary vertex (PV), which is defined as the vertex with the largest sum of squared transverse momenta of associated tracks, must satisfy $|z_0 \sin\theta| < 0.5$ mm. The transverse impact parameter d_0 of the associated track must satisfy $|d_0/\sigma_{d_0}| < 6$, where σ_{d_0} is the uncertainty on the measurement of d_0. To reduce the background due to jets misidentified as electrons, electron candidates are required to be isolated in both the calorimeter and the ID. The isolation requirements are $R^{\mathrm{iso}}_{\mathrm{Cal}} < 0.16$ and $R^{\mathrm{iso}}_{\mathrm{ID}} < 0.16$, where $R^{\mathrm{iso}}_{\mathrm{Cal}}$ is the total transverse energy recorded in the calorimeters within a cone of size $\Delta R = 0.3$ around the lepton direction, excluding the energy of the lepton itself, divided by the lepton E_{T}, and $R^{\mathrm{iso}}_{\mathrm{ID}}$ is the sum of the p_{T} of the tracks in a cone of size $\Delta R = 0.3$ around the lepton direction, excluding the track of the lepton, divided by the lepton p_{T}.

Muon candidates are reconstructed within the range $|\eta| < 2.5$ by combining tracks in the ID and the MS. Robust reconstruction is ensured by requiring a minimum number of hits in each of the sub-detectors of ID to be associated with the reconstructed ID tracks. Moreover, the muon reconstructed track must satisfy the requirements $|z_0 \sin\theta| < 0.5$ mm and $|d_0/\sigma_{d_0}| < 3.5$. The measured momenta in the ID and the MS are required to be consistent with each other by satisfying $|(q/p)^{\mathrm{ID}} - (q/p)^{\mathrm{MS}}| < 5\sigma$, where $(q/p)^{\mathrm{ID}}$ and $(q/p)^{\mathrm{MS}}$ are the charge q over momentum p in the ID and the MS respectively, and σ is the total uncertainty on the difference between q/p measurements in the ID and the MS. The muon isolation requirements are $R^{\mathrm{iso}}_{\mathrm{Cal}} < 0.2$ and $R^{\mathrm{iso}}_{\mathrm{ID}} < 0.15$.

When the Z boson has high momentum ($\gtrsim 600$ GeV), its collimated lepton decay products can be within a cone of size $\Delta R = 0.3$. To maintain a high efficiency for high-mass signals the isolation requirements imposed on the leptons are modified to not include in the calculation of $R^{\mathrm{iso}}_{\mathrm{Cal}}$ and $R^{\mathrm{iso}}_{\mathrm{ID}}$ the energy and momenta of any close-by same-flavour leptons. For an $m_{W'} = 1.4$ TeV signal, the relative efficiency gain, with respect to the selection without modifying the isolation requirements, is of the order of 60%. Finally, to reduce photon conversion backgrounds from muon radiation, if a muon and an electron are separated by less than $\Delta R = 0.1$ from each other, the electron candidate is discarded.

The missing transverse momentum, with magnitude $E^{\mathrm{miss}}_{\mathrm{T}}$, is the momentum imbalance in the transverse plane. The $E^{\mathrm{miss}}_{\mathrm{T}}$ is calculated from the negative vector sum of the transverse momenta of all reconstructed objects, including muons, electrons, photons and jets, as well as clusters of calorimeter cells not associated with these objects [45].

Attributing the $E^{\mathrm{miss}}_{\mathrm{T}}$ to the transverse component of the neutrino momentum, its longitudinal component (p^{ν}_{z}) is derived by requiring that the neutrino and the lepton attributed to the W boson decay have an invariant mass equal to the pole mass of the W boson: 80.385 GeV [46]. This constraint results in a quadratic equation with two solutions for p^{ν}_{z}. If the solutions are real the one with the smaller absolute value is kept. If the solutions are complex only the real part is kept. In general, about 30% of the events are found to have complex solutions, mainly due to the $E^{\mathrm{miss}}_{\mathrm{T}}$ resolution at the reconstruction level. The invariant mass of the $WZ \to \ell\nu\ell'\ell'$ system is reconstructed from the four-vectors of the candidate W and Z bosons and is used as the discriminating variable for the signal.

5. Event selection

The PV of the event must have at least three associated tracks with $p_{\mathrm{T}} > 0.4$ GeV. Candidate $WZ \to \ell\nu\ell'\ell'$ events are then required to have exactly three charged leptons with $p_{\mathrm{T}} > 25$ GeV and $E^{\mathrm{miss}}_{\mathrm{T}} > 25$ GeV. Events are rejected if a fourth lepton is found with $p_{\mathrm{T}} > 20$ GeV. At least one of the three leptons is required to be geometrically matched to an object that fired the trigger. Two opposite-sign same-flavour leptons are required to have an invariant mass ($m_{\ell\ell}$) within 20 GeV of the Z boson pole mass: 91.1875 GeV [47]. If two possibilities exist, the pair that has $m_{\ell\ell}$ closest to the Z boson pole mass is chosen to form the Z candidate. To suppress the Z + jets background where one jet is reconstructed as an isolated electron, the electrons used in the reconstruction of the W bosons are required to satisfy tighter identification criteria (`tight`) than those required for the leptons used in the reconstruction of Z boson decays (`medium`). These stricter criteria are described in Ref. [44].

To improve the sensitivity to resonant signals, events are further required to have $\Delta y(W, Z) < 1.5$, where $\Delta y(W, Z)$ is the rapidity[2] difference between the W and Z bosons. This selection has an efficiency exceeding 82% for all W' masses and reaching 94% for $m_{W'} = 200$ GeV.

Finally, two signal regions are defined, one more sensitive for high-mass W' signals ($m_{W'} \gtrsim 250$ GeV) and the other one for low-mass W' signals ($m_{W'} \lesssim 250$ GeV). The high-mass signal region ($\mathrm{SR_{HM}}$) is defined by the additional requirement $\Delta\phi(\ell, E^{\mathrm{miss}}_{\mathrm{T}}) < 1.5$, where $\Delta\phi(\ell, E^{\mathrm{miss}}_{\mathrm{T}})$ is the azimuthal angle between the lepton attributed to the W candidate decay and the missing transverse momentum vector. Conversely, the low-mass signal region ($\mathrm{SR_{LM}}$) is required to have $\Delta\phi(\ell, E^{\mathrm{miss}}_{\mathrm{T}}) > 1.5$, which has high acceptance for low-mass signals.

6. Background estimations

The major backgrounds come from the SM WZ, ZZ and $t\bar{t} + W/Z$ processes with at least three prompt leptons in the final state. A control region dominated by SM WZ events ($\mathrm{CR_{SMWZ}}$) is defined to check the modelling of the MC predictions for these backgrounds. The selection criteria used for this region are similar to those for the signal regions except that the requirement on $\Delta y(W, Z)$ is reversed and the requirement on $\Delta\phi(\ell, E^{\mathrm{miss}}_{\mathrm{T}})$ is removed. The reversal of the $\Delta y(W, Z)$ selection reduces possible signal contamination to negligible levels, assuming previous exclusion results [23,27]. In total, 323 events are observed in data for all four channels combined and the SM backgrounds are expected to be $298 \pm 4(\mathrm{stat.}) \pm 26(\mathrm{syst.})$ events, where the computation of the systematic uncertainties is detailed in Section 7. Good agreement is also found between data and the SM predictions in the shapes of various kinematical distributions. The m_{WZ} distribution in the SM WZ control region is shown in Fig. 1.

Contributions from the $\ell\ell'$ + jets background, where at least one lepton originates from hadronic jets, are estimated using a data-driven method. A lepton-like jet is defined as a jet that is reconstructed as a lepton and satisfies all lepton selection criteria but, in the muon case, fails either the calorimeter or track isolation requirement, or, in the electron case, fails the isolation or `medium` quality requirement but passes a looser set of electron identification quality requirements. A "fake factor", defined as the number of events in which a jet satisfies the nominal lepton selection criteria divided by the number of events in which a jet satisfies the lepton-like jet criteria, is computed. It can be interpreted as the probability that a lepton-like jet is instead reconstructed as a nominal lepton. The fake background is dominated by events with one jet misidentified as an isolated lepton, while contributions from other processes with two or three jets misidentified as isolated

[2] Rapidity is defined as $y = (1/2)\ln[(E + p_z)/(E - p_z)]$.

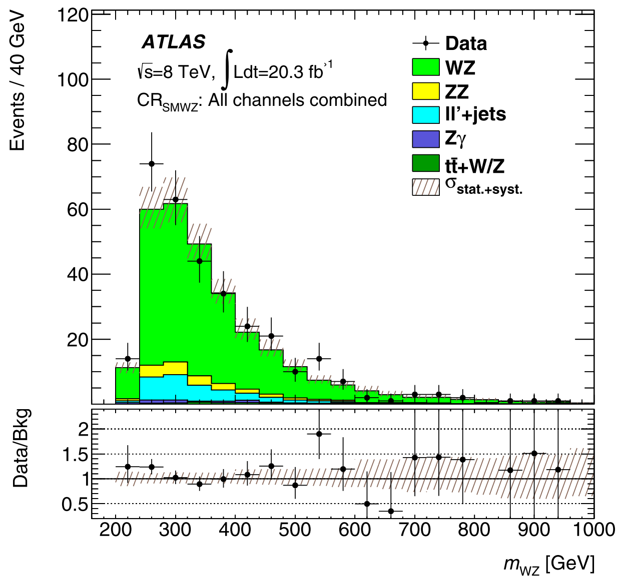

Fig. 1. Distribution of WZ invariant mass (m_{WZ}) in the SM WZ control region (CR_{SMWZ}) for the four $\ell\nu\ell'\ell'$ channels combined. The uncertainty bands upon the expected background include both the statistical and systematic uncertainties in the MC simulation and the fake-background estimation added in quadrature.

leptons are found to be negligible. The fake background is thus estimated by applying the fake factor to a data sample (denoted as "tight + loose sample") selected using all signal selection criteria except for a requirement that one of the three leptons must be a lepton-like jet. Since the electron identification and isolation requirements are different for those coming from a Z or a W candidate decay, the electron fake factor is calculated separately for these two cases.

The lepton fake factor is measured in two different data samples: dijet and Z + jets events. In both cases the tag-and-probe method [48,49] is used, but the tag objects are different. The larger number of events within the dijet sample permits a measurement of the dependence of the lepton fake factor on the lepton p_T or η. Using the Z + jets sample, on the other hand, leads to a measurement where the kinematic distributions and flavour compositions are closer to that of the signal region, albeit with significantly fewer events allowing only a measurement of the fake factor as a single number.

In the tight + loose sample and the two samples used for the fake-factor measurement, the backgrounds containing prompt leptons are estimated using MC simulation and subtracted from the data samples. These include the production of Z + jets simulated with ALPGEN 2.14 [50], $t\bar{t}$ with MC@NLO 4.03 [51], W + jets and $W\gamma$ with ALPGEN, as well as the previously mentioned WZ, ZZ, $Z\gamma$, and $t\bar{t} + W/Z$ MC samples. The parton showering is modelled by HERWIG/JIMMY [52,53] for Z + jets, $t\bar{t}$, W + jets, and $W\gamma$ events. The events remaining after subtraction are thus the expected lepton yields due to misidentified jets.

The dijet sample is selected with one tag jet and one probe jet that are almost back-to-back, with $\Delta\phi > 2.5$. The tag jets are normal hadronic jets and the probe jet is required to satisfy the selection criteria for a lepton-like jet or a nominal lepton. The tag jets are reconstructed up to $|\eta| = 4.5$ from calorimeter clusters with the anti-k_t algorithm [54] using a distance parameter of 0.4 and are calibrated to the hadronic energy scale. They are required to have $p_T > 25$ GeV. For jets with $p_T < 50$ GeV and $|\eta| < 2.4$, the scalar p_T sum of the tracks that are associated with the PV and that fall into the jet area must be at least 50% of the scalar p_T sum of all tracks falling into the same jet area. The dijet events are selected by single-muon and single-photon triggers, with p_T and E_T thresholds of 24 and 20 GeV in the muon and electron cases respectively. The muon/electron requirements at the trigger level are looser than the lepton-like jet selection criteria in order to allow for an unbiased measurement of the lepton fake factor. To better mimic the kinematic properties of the signal region, the E_T^{miss} is required to be higher than 25 GeV, which also helps reject the Z + jets background. The probe jet and the missing transverse momentum are required to have a transverse mass smaller than 40 GeV to suppress the W + jets background. The probe jet is then examined to determine whether it satisfies the nominal lepton selection criteria or those of the lepton-like jet.

The Z + jets sample is defined as having one same-flavour opposite-charge lepton pair consistent with the Z boson decay as the tagged object, and a probe jet that satisfies the selection criteria for a lepton-like jet or a nominal lepton. They are selected by a set of single-lepton and dilepton triggers to improve the trigger efficiency. To suppress the contribution from prompt leptons from WZ production, events are required to have $E_T^{miss} < 25$ GeV. The probe jet is used for measuring the fake factor.

In both the dijet and Z + jets samples, several sources of systematic uncertainty for the measurement of the fake factors are considered, stemming from the trigger bias, kinematic and flavour differences with respect to the signal region, the E_T^{miss} threshold requirement, and prompt-lepton subtraction. In the dijet sample, possible biases related to the tag-jet p_T threshold, the transverse mass requirement on the probe jet and E_T^{miss} system, and the azimuthal angle between the tag jet and the probe jet are also considered. Likewise, additional biases associated with the measurement in the Z + jets sample, such as potential systematic kinematic differences between the low- and high-E_T^{miss} regions, are also considered. The total uncertainties on the fake factors measured using the dijet sample ranges from 8% to 33% for muons with $p_T < 50$ GeV and electrons with $p_T < 70$ GeV. Beyond the above p_T ranges the fake factors are assigned a $\gtrsim 100\%$ systematic uncertainty due to the subtraction of prompt backgrounds. The total uncertainties on the fake factors measured using the Z + jets sample range from 27% to 36% for different lepton flavours and definitions. The uncertainties on the fake factors are applied to the fake-background estimate as normalization uncertainties.

The fake factors, which are of the order of 0.1 for both lepton flavours, are measured in both samples. The p_T-binned central values from the dijet sample measurement are the ones used in this analysis. The differences between the fake factors from the two samples can be up to $\sim 60\%$ and are the dominant contributions to the fake-factor uncertainty.

The observed and predicted background event yields are compared in an $\ell\ell'$ + jets-enriched control region ($CR_{\ell\ell'+\text{jets}}$) where events are required to have the same lepton selection and Z mass requirement as in the nominal signal selection but with E_T^{miss} less than 25 GeV and the transverse mass of the W candidate less than 25 GeV. In this region, a total of 204 events are observed in data with an SM expectation of $195 \pm 4(\text{stat.}) \pm 38(\text{syst.})$ events. Good agreement is found between observed data and estimated background for various kinematic distributions. The Z candidate invariant mass distribution is shown in Fig. 2.

7. Systematic uncertainties

Relative uncertainties on the expected yields of the dominant WZ background and the EGM W' signal with $m_{W'} = 1$ TeV in SR_{HM} are shown in Table 2. These uncertainties are representative of those found for other signal masses and background types. The lepton-related ones include uncertainties from the lepton trigger, identification, energy scale, energy resolution, isolation, and impact

Table 2
Relative uncertainties in the expected yields for the SM WZ background and the EGM W' signal with $m_{W'} = 1$ TeV in the high-mass signal region (SR_{HM}). The renormalization and factorization scales, together with the PDF uncertainties on the fiducial cross section are included under theoretical uncertainty for SM WZ background. For EGM W' signal, the theoretical uncertainty stands for the effects of the scale and PDF uncertainties, added in quadrature, on its acceptance. Shape-related uncertainties are not included here. Similar results are found in the low-mass signal region (SR_{LM}).

Uncertainty sources	SM WZ				EGM W' ($m_{W'} = 1$ TeV)			
	$evee$	μvee	$ev\mu\mu$	$\mu v\mu\mu$	$evee$	μvee	$ev\mu\mu$	$\mu v\mu\mu$
MC statistics	2.7%	2.0%	2.0%	2.2%	2.5%	2.5%	2.5%	2.5%
Lepton-related	3.1%	2.1%	1.8%	1.9%	3.7%	2.6%	2.1%	2.4%
E_T^{miss}-related	2.8%	1.9%	2.6%	1.7%	1.1%	0.4%	0.4%	0.4%
Luminosity	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%
Theory	9.5%	9.5%	9.5%	9.5%	0.6%	0.5%	0.2%	0.2%

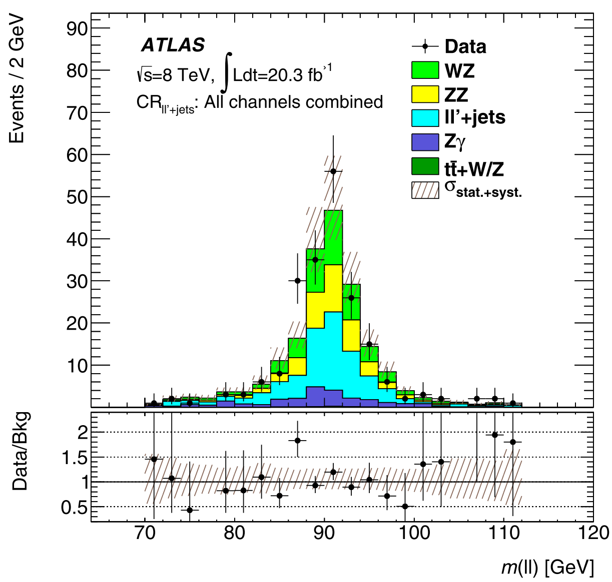

Fig. 2. Z candidate invariant mass distribution in the $\ell\ell' +$ jets background control region ($CR_{\ell\ell'+jets}$). The uncertainty bands upon the expected background include both the statistical and systematic uncertainties in the MC simulation and the fake-background estimation added in quadrature.

parameters. The uncertainties on the lepton momentum and jet energy scales and resolutions are propagated to the E_T^{miss} calculation. Other E_T^{miss}-related uncertainties include those on soft energy deposits due to additional pp collisions, and energy deposits not associated with any reconstructed object. Both the normalization and shape uncertainties are taken into account from the above sources.

Cross-section uncertainties for the dominant SM physics processes are computed via MCFM [55], which provides NLO QCD calculations for diboson production cross sections. The relative uncertainty due to higher-order corrections to the WZ cross sections is 5% [56]. The renormalization and factorization scales are varied by a factor of two relative to their nominal values. The resulting sum in quadrature of the uncertainties in SR_{HM} on the WZ, ZZ, and $Z\gamma$ cross sections are found to be 6.9%, 4.3%, and 5.0% respectively. PDF uncertainties are derived by comparing the predicted cross sections using the NLO CT10 and MSTW PDF as well as the CT10 eigenvector error PDF sets (90% confidence level). The resulting uncertainties are 4.1%, 4.7% and 3.2% for these three processes respectively.

Given that the SM background modelling suffers from low MC event counts in the tail of the m_{WZ} distribution, an extrapolation method is devised to smooth the predicted yields. The method consists in performing two independent χ^2 fits, one on the WZ background in the region with $m_{WZ} > 500$ GeV, and a second on the sum of all non-WZ backgrounds in the region with $m_{WZ} > 300$ GeV, each with the power-law function $N(x) = c_0 x^{c_1}$, where x is m_{WZ}. The overall normalization of the fitted function is set to the expected number of events for each of the two types of background. The non-WZ backgrounds are fitted jointly to gain from their combined size, thus reducing the total uncertainty in the fit, which is computed via the minimization function's Hessian error matrix. Other fitting functions such as an exponential or more elaborate power-law functions were tested, but their shapes were found to be within the uncertainties from the simple power-law function given above. Hence, only the uncertainties from the simple power-law function are considered, and these dominate all other uncertainties in the range $m_{WZ} > 800$ GeV (e.g. the fit uncertainty reaches 50% of the total expected yields at $m_{WZ} = 800$ GeV, and 400% at $m_{WZ} = 1.6$ TeV).

Additionally, the shapes of the m_{WZ} distribution for the SM WZ process predicted by POWHEG-BOX and the multi-leg generators SHERPA and MadGraph, as well as NLO generators such as MC@NLO are compared. The largest deviations from the POWHEG-BOX distribution are used as systematic uncertainties on the predicted m_{WZ} shape.

A procedure was developed to obtain the m_{WZ} distribution for any given $m_{W'}$ mass point using a functional interpolation between the available m_{WZ} signal templates. These distributions are individually fitted with a crystal ball function using RooFit [57]. The 4 crystal ball parameters are then each fitted as a function of the W' mass to build the m_{WZ} template for any intermediate W' mass point. All systematic uncertainties are individually interpolated.

Theoretical uncertainties on the EGM W' signal yields primarily come from uncertainties on the reconstructed signal's acceptance times efficiency due to the PDF set used. The uncertainties in the signal acceptance due to the PDF are derived from the MSTW eigenvector error sets, and the difference between the predictions of the CT10 and MSTW PDF sets, combined in quadrature.

8. Results

The m_{WZ} spectrum in the two signal regions is scrutinized for excesses of data over the predicted SM backgrounds. A total of 449 WZ candidate events in SR_{HM} are observed in the data after applying all event selection criteria, to be compared with the SM prediction of $421 \pm 5(\text{stat.})^{+56}_{-39}(\text{syst.})$ events. The corresponding numbers in SR_{LM} are 617 events selected in the data and $563 \pm 5(\text{stat.})^{+55}_{-43}(\text{syst.})$ events expected from SM processes. The observed m_{WZ} distribution in SR_{HM} is compared to the expected SM background distribution in Fig. 3, which combines all four lepton decay channels. The contributions from hypothetical EGM W' bosons with masses of 600, 1000, and 1400 GeV are also shown. A breakdown of the signal, backgrounds, and observed data yields in SR_{HM} is shown in Table 3 for each individual channel and also for all four channels combined. The m_{WZ} distribution in SR_{LM} is shown in Fig. 4.

Table 3
The estimated background yields, the observed number of data events, and the predicted signal yield for a set of W' resonance masses in the high-mass signal region (SR_{HM}).

	$e\nu ee$	$\mu\nu ee$	$e\nu\mu\mu$	$\mu\nu\mu\mu$	Combined
Backgrounds:					
WZ	$56.5 \pm 1.5 \pm 6.1$	$68.6 \pm 1.4 \pm 7.0$	$70.1 \pm 1.4 \pm 7.2$	$89.8 \pm 2.0 \pm 9.1$	$285 \pm 3 \pm 29$
ZZ	$8.7 \pm 0.1 \pm 0.9$	$8.7 \pm 0.2 \pm 0.8$	$11.7 \pm 0.2 \pm 1.3$	$11.6 \pm 0.2 \pm 1.1$	$40.7 \pm 0.4 \pm 3.9$
$Z\gamma$	$6.4 \pm 0.8 \pm 1.5$	< 0.05	$8.1 \pm 0.9 \pm 1.2$	< 0.05	$14.5 \pm 1.2 \pm 2.2$
$t\bar{t} + W/Z$	$2.5 \pm 0.1 \pm 0.8$	$3.2 \pm 0.1 \pm 1.0$	$2.6 \pm 0.1 \pm 0.8$	$3.3 \pm 0.1 \pm 1.0$	$11.6 \pm 0.2 \pm 3.5$
$\ell\ell' + \text{jets}$	$12.7 \pm 1.0^{+8.9}_{-5.6}$	$19 \pm 2^{+11}_{-4}$	$14 \pm 1^{+13}_{-7}$	$23 \pm 2^{+15}_{-7}$	$69 \pm 3^{+47}_{-24}$
Sum of backgrounds	$87 \pm 2^{+11}_{-9}$	$100 \pm 2^{+13}_{-8}$	$107 \pm 2^{+15}_{-11}$	$128 \pm 3^{+18}_{-12}$	$421 \pm 5^{+56}_{-39}$
Data	99	90	136	124	449
Signals:					
$W' \to WZ$ ($M(W') = 600$ GeV)	$54.2 \pm 1.6 \pm 2.7$	$62.2 \pm 1.7 \pm 3.1$	$59.9 \pm 1.7 \pm 3.0$	$68.2 \pm 1.8 \pm 3.4$	$244 \pm 3 \pm 12$
$W' \to WZ$ ($M(W') = 1000$ GeV)	$7.1 \pm 0.2 \pm 0.4$	$7.4 \pm 0.2 \pm 0.4$	$7.1 \pm 0.2 \pm 0.4$	$7.1 \pm 0.2 \pm 0.4$	$28.6 \pm 0.4 \pm 1.3$
$W' \to WZ$ ($M(W') = 1400$ GeV)	$1.3 \pm 0.1 \pm 0.1$	$1.3 \pm 0.1 \pm 0.1$	$1.3 \pm 0.1 \pm 0.1$	$1.2 \pm 0.1 \pm 0.1$	$5.1 \pm 0.1 \pm 0.2$

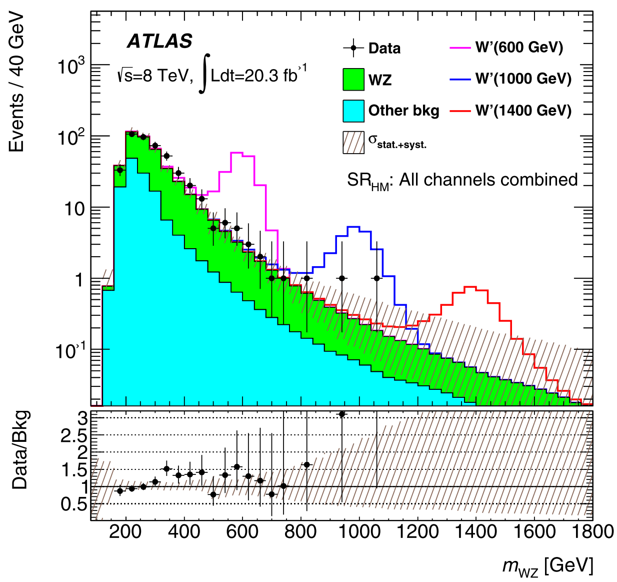

Fig. 3. Observed and predicted WZ invariant mass (m_{WZ}) distribution for events in the high-mass signal region (SR_{HM}). An extrapolation of the backgrounds to the very-high-mass region was performed using a power-law function to fit for the SM WZ and the sum of all other backgrounds separately. Predictions from W' samples with masses of 600 GeV, 1000 GeV and 1400 GeV are also shown, stacked on top of the expected backgrounds. The uncertainty bands upon the expected background include both the statistical and systematic uncertainties in the MC simulation and the fake-background estimation added in quadrature.

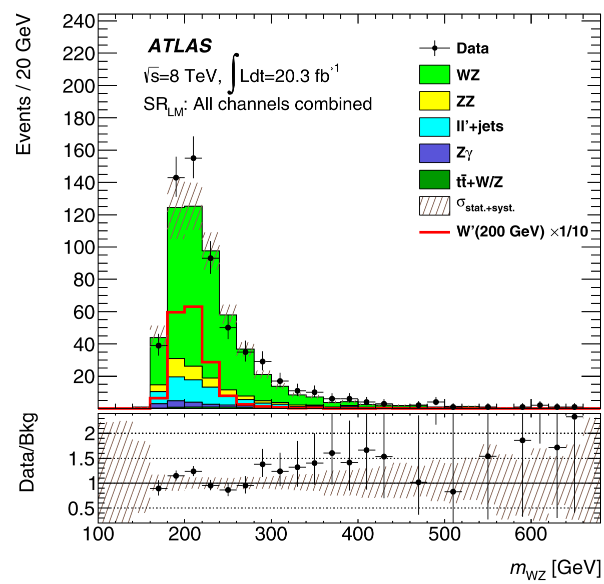

Fig. 4. Observed and predicted WZ invariant mass (m_{WZ}) distribution for events in the low-mass signal region (SR_{LM}). Predictions from a W' sample with mass of 200 GeV are also shown. The W' curve is scaled by 1/10 for better display. The uncertainty bands upon the expected background include both the statistical and systematic uncertainties in the MC simulation and the fake-background estimation added in quadrature.

The m_{WZ} distribution is used to build a binned log-likelihood ratio (LLR) test statistic [58]. The systematic uncertainties are represented by nuisance parameters for both the backgrounds and signals. Confidence levels (CL) for the signal-plus-background hypothesis ($\text{CL}_{\text{s+b}}$) and background-only hypothesis (CL_{b}) are computed by integrating the LLR distributions obtained from simulated pseudo-experiments using Poisson statistics.

To check the consistency between the observed data and expected SM backgrounds, the p-value, defined as $1 - \text{CL}_{\text{b}}$, for a background fluctuation to give rise to an excess at least as large as that observed in data is computed. The obtained p-values are reported in Table 4 for the signal hypothesis of a W' particle with mass from 200 GeV to 2 TeV. The lowest local p-value probability is found to be 8% for the 375 GeV resonance mass hypothesis, equivalent to a 1.75σ local excess, indicating that no significant excess is observed.

In the modified frequentist approach [59], the 95% CL excluded cross section is computed as the cross section for which CL_{s}, defined as the ratio $\text{CL}_{\text{s+b}}/\text{CL}_{\text{b}}$, is equal to 0.05. For the mass points above 400 GeV, only the high-mass signal region is used in the calculation by statistically combining all lepton decay channels. For the mass points below or equal to 400 GeV, the two signal regions are further combined to maximize the sensitivity of the search.

Fig. 5 presents the 95% CL upper limits on $\sigma(pp \to X) \times \text{B}(X \to WZ)$ as a function of the signal resonance mass, where X stands for the signal resonance, together with the theoretical cross sections of the EGM W' and HVT benchmark models. The latter cross sections are calculated via the web interface [60] provided by the authors of Ref. [20]. The exclusion region in parameter space $\{(g^2/g_V)c_F, g_V c_H\}$ is shown in Fig. 6. The fermion coupling c_F was set to the same value for quarks and leptons. The couplings c_{VVV}, c_{VVHH} and c_{VVW}, which involve vertices with more than one heavy vector boson and which have negligible effect on the cross section, were set to zero. Table 4 presents the expected and observed limits for a selected set of signal mass points as well as the EGM W' signal acceptance A and correction factor C. The acceptance A is defined as the number of generated events found within the fiducial region at particle level divided by the total number of generated events, while C is defined as the number of reconstructed events passing the nominal selection requirements divided by the number of generated events within the fiducial region at particle level. The fiducial region selection criteria consist of the same kinematic se-

Table 4
The expected and observed 95% CL upper limits on the production cross section of narrow resonances decaying to WZ as a function of their mass. The high-mass signal region (SR_{HM}) and low-mass signal region (SR_{LM}) fiducial acceptances at particle level (A) and correction factors (C) for an EGM W' as implemented in PYTHIA are also given. SR_{LM} was not used in setting the limits for the mass points beyond 400 GeV due to their very low acceptances. Errors shown are statistical. The p-value, defined as $1 - CL_b$, is also shown for each mass point in the last column.

$m_{W'}$ [GeV]	Excluded $\sigma \times$ B [fb]		SR_{HM} A/C	SR_{LM} A/C	p-value
	Expected	Observed			
200	2613	3182	$0.025 \pm 0.001/0.75 \pm 0.05$	$0.135 \pm 0.003/0.57 \pm 0.02$	0.36
250	1902	1853	$0.111 \pm 0.002/0.55 \pm 0.02$	$0.070 \pm 0.002/0.80 \pm 0.03$	0.48
300	751	1195	$0.202 \pm 0.003/0.57 \pm 0.01$	$0.024 \pm 0.001/1.42 \pm 0.07$	0.22
350	427	894	$0.269 \pm 0.004/0.61 \pm 0.01$	$0.0093 \pm 0.0006/2.5 \pm 0.2$	0.094
375	330	670	$0.29 \pm 0.01/0.62 \pm 0.02$	$0.007 \pm 0.001/2.9 \pm 0.6$	0.080
400	281	526	$0.311 \pm 0.005/0.63 \pm 0.01$	$0.0048 \pm 0.0005/3.3 \pm 0.4$	0.094
600	90	115	$0.426 \pm 0.006/0.68 \pm 0.01$		0.29
800	52	40	$0.475 \pm 0.006/0.68 \pm 0.01$		0.71
1000	38	33	$0.505 \pm 0.007/0.68 \pm 0.01$		0.59
1200	31	24	$0.526 \pm 0.007/0.66 \pm 0.01$		0.71
1400	25	21	$0.530 \pm 0.007/0.66 \pm 0.01$	*not used*	0.81
1600	23	21	$0.533 \pm 0.007/0.63 \pm 0.01$		0.83
1800	23	21	$0.544 \pm 0.007/0.60 \pm 0.01$		0.82
2000	24	22	$0.535 \pm 0.007/0.57 \pm 0.01$		0.85

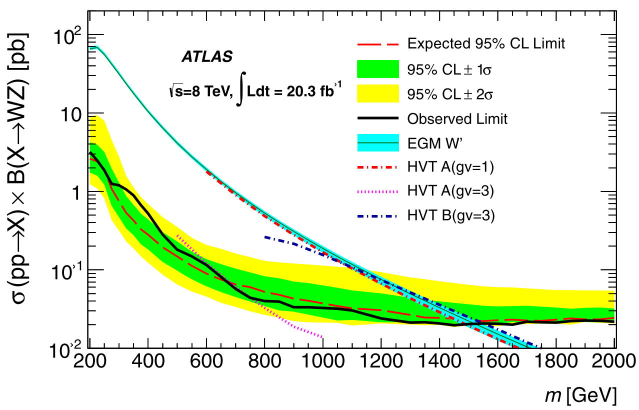

Fig. 5. The observed 95% CL upper limits on $\sigma(pp \to X) \times B(X \to WZ)$ as a function of the signal mass m, where X stands for the signal resonance. The expected limits are also shown together with the ± 1 and ± 2 standard deviation uncertainty bands. Both the expected and observed upper limits assume the EGM W' signal acceptance times efficiency as presented in Table 4. Theoretical cross sections for the EGM W' and the HVT benchmark models are also shown. The uncertainty band around the EGM W' cross-section line represents the theoretical uncertainty on the NNLO cross-section calculation using ZWPROD [32].

lections (lepton p_T, lepton η, Z boson mass, E_T^{miss}, $\Delta y(W, Z)$ and $\Delta\phi(\ell, E_T^{miss})$) and lepton isolation requirements as in the nominal selections. Particle level refers to particle states that stem from the hard scatter, including those that are the product of hadronization, but before their interaction with the detector. Table 5 presents the 95% CL expected and observed lower limits on the EGM W' boson mass for each decay channel and their combination. The observed (expected) exclusion limit on the EGM W' mass is found to be 1.52 (1.49) TeV, and the limits in each channel are shown in Table 5. The simulated HVT resonances are found to have kinematic distributions similar to those of the W' and thus have similar acceptances to the EGM model. The corresponding observed (expected) limits for the $A(g_V = 1)$, $A(g_V = 3)$, and $B(g_V = 3)$ HVT resonances from Ref. [20] are 1.49 (1.45) TeV, 0.76 (0.69) TeV, and 1.56 (1.53) TeV respectively. In Fig. 5, the HVT benchmark model curves are not shown for low resonance mass where the models do not apply.

9. Conclusion

A search for resonant WZ diboson production in the fully leptonic channel has been performed with the ATLAS detector, using 20.3 fb^{-1} of pp collision data collected at $\sqrt{s} = 8$ TeV at the LHC.

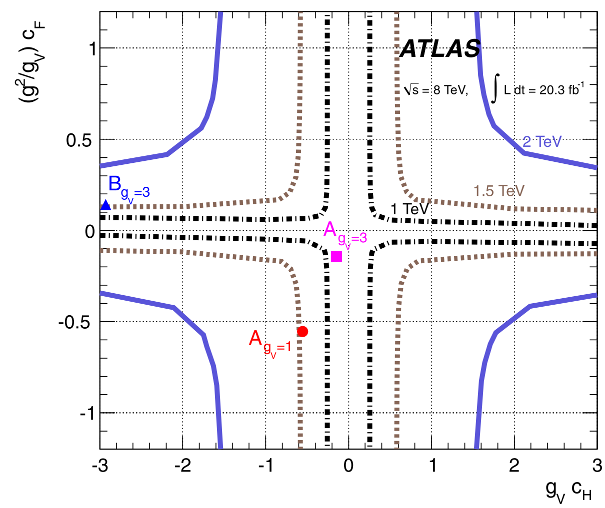

Fig. 6. Observed 95% CL exclusion contours in the HVT parameter space $\{(g^2/g_V)c_F, g_V c_H\}$ for resonances of mass 1 TeV, 1.5 TeV and 2 TeV. Also shown are the benchmark model parameters $A_{(g_V=1)}$ (circle) and $A_{(g_V=3)}$ (square) and $B_{(g_V=3)}$ (triangle).

Table 5
Expected and observed lower mass limits at 95% CL in TeV for the EGM W' boson in the $e\nu ee$, $e\nu\mu\mu$, $\mu\nu ee$, $\mu\nu\mu\mu$ channels as well as the four channels combined.

	Excluded EGM W' lower mass [TeV]				
	$e\nu ee$	$\mu\nu ee$	$e\nu\mu\mu$	$\mu\nu\mu\mu$	combined
Expected	1.21	1.16	1.17	1.16	1.49
Observed	1.20	1.19	1.06	1.17	1.52

No excess is found in data compared to the SM expectations. Stringent limits on the production cross section times WZ branching ratio are obtained as a function of the resonance mass for a W' arising from an extended gauge model and decaying to WZ. A corresponding observed (expected) mass limit of 1.52 (1.49) TeV is derived for the W'.

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