Measurement of the W±Z production cross section and limits on anomalous triple gauge couplings in proton-proton collisions at √s = 7 TeV with the ATLAS detector


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Measurement of the $W^\pm Z$ production cross section and limits on anomalous triple gauge couplings in proton–proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

The underlying structure of the electroweak interactions in the Standard Model (SM) is the non-abelian SU(2)$_L \times$ U(1)$_Y$ gauge group. Properties of electroweak gauge bosons such as their masses and couplings to fermions have been precisely measured at LEP and the Tevatron [1]. However, triple gauge boson couplings (TGC) predicted by this theory have not yet been determined with comparable precision.

In the SM the triple gauge boson vertex is completely fixed by the electroweak gauge structure. A measurement of this vertex, for example through the analysis of diboson production at the LHC, tests the gauge symmetry and probes for possible new phenomena involving gauge bosons. In general, electroweak boson couplings deviating from gauge constraints yield enhancements of phenomena involving gauge bosons. In general, electroweak boson couplings deviating from gauge constraints yield enhancements of the $W^\pm Z$ production cross section at high diboson invariant mass.

Furthermore, new particles decaying into $W^\pm Z$ pairs are predicted in models with extra vector bosons (e.g. $W'$) as well as in supersymmetric models with an extended Higgs sector (charged Higgs) [2,3].

At the LHC, the dominant $W^\pm Z$ production mechanism is from quark–antiquark and quark–gluon interactions at leading order (LO) and at next-to-leading order (NLO), respectively [4]. Only the s-channel diagram has a triple electroweak gauge boson interaction vertex and is hence the only channel that may contribute to anomalous TGC (aTGC).

This Letter presents a measurement of the $W^\pm Z$ production cross section and limits on aTGC with the ATLAS detector in LHC proton–proton collisions at a centre-of-mass energy, $\sqrt{s}$, of 7 TeV. The analysis uses four channels with leptonic decays ($W^\pm Z \rightarrow \ell\nu\ell\nu$) involving electrons and muons: $ee\mu\nu$, $e\nu\mu\mu$, or $\mu\nu\mu\nu$, where the $\ell$ is estimated by the missing transverse momentum, $E_T^{\rm miss}$. The main sources of background are $ZZ$, $Z\gamma$, $Z +$ jets, and top-quark events.

A common phase space is defined for combining the four decay channels and measuring a “fiducial” cross section. The phase space is chosen to match closely the detector acceptance and analysis selection. The lepton from the $Z$ and $W$ boson decays are required to have transverse momenta $p_T^\ell > 20$ GeV, pseudorapidity $|\eta^\ell| < 2.5$, $|m_{\ell\ell}(Z)-m_Z| < 10$ GeV, $p_T^W > 25$ GeV and the transverse mass \(^2\) of the $W$ boson is required to satisfy $m_T^W > 20$ GeV. Final state electrons and muons whose four-momenta include all photons within $\Delta R < 0.1$ are used in the phase space definition. Since the fiducial phase space is defined by the lepton kinematics, the cross section definition includes the branching ratios of the bosons decaying into electrons or muons. The fiducial cross section definition excludes the contribution from $W$ and $Z$ boson decays into $\tau$ leptons.

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the interaction point to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ as $\eta = -\ln(\tan(\theta/2))$.

2. The transverse mass is defined as $m_T^2 = 2E_T^\ell p_T^\ell - p_T^\ell p_T^\ell$.

3. $\Delta R$ is defined as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. 
In order to measure the total cross section, the experimentally accessible phase space is extrapolated to the full phase space. The region dominated by the contribution of a $γ^*γ^*$ propagator in singly resonant diagrams to the theoretical cross section is highly suppressed by requiring the invariant mass of the dilepton system from $Z/γ^*$ to satisfy $66 \text{ GeV} < m_{γ^*} < 116 \text{ GeV}$ for the full phase space.

In the SM the only allowed boson combinations for TGC vertices are $WWγ$ and $WWWZ$, and the latter is addressed in this Letter. Expressions for the most general effective Lagrangian for a TGC vertex with two charged and one neutral vector boson can be found in Refs. [5] and [6]. If only terms that separately conserve charge conjugation and parity are considered, then the couplings can be represented by three dimensionless parameters $g_1^Z$, $g_2^Z$, and $λ_2$. In the SM $g_1^Z = 1$, $g_2^Z = 1$ and $λ_2 = 0$. Anomalous couplings, defined as deviations from these SM values, are then $Δg_1^Z$, $Δg_2^Z$ and $Δλ_2$.

To avoid tree-level unitarity violation, which occurs in the effective Lagrangian approach at sufficiently large energies, the anomalous couplings must be suppressed at higher energy scales. To achieve this, an arbitrary form factor can be introduced to mitigate the effect of anomalous couplings at higher energy scales. For comparison with previous studies, results are presented using a dipole form factor $f(\hat{s}) = 1/(1 + \hat{s}/λ^2)$, where $λ = 2 \text{ TeV}$ is a cut-off energy scale and $\sqrt{\hat{s}}$ is the partonic centre-of-mass energy.

This choice ensures that unitarity is not violated. However, since the choice of the scale is arbitrary and the experimental centre-of-mass energy scale is finite, the interpretation of the data in the framework of anomalous couplings is also presented without using a form factor, corresponding to setting $λ = \infty$.

3. Object reconstruction

The main physics objects necessary to select $W^±Z$ events are electrons, muons, and $E_{\text{miss}}$. Muons are identified by matching tracks reconstructed in the MS to tracks reconstructed in the ID. Their momenta are calculated by combining information from the two tracks and correcting for energy deposited in the calorimeter.

Muons are tracked in the ID using a silicon vertex detector, a inner tracking detector, a transition radiation tracker, and a muon spectrometer. These detectors provide precise measurement of the tracks and angular momenta. The muon momentum is calculated by combining information from the ID, MS, and TRT detectors. To avoid the transition region between the ID and MS, muons are only considered if their momentum is within the ID range.

Electrons are reconstructed by matching clusters found in the electromagnetic calorimeter to tracks in the ID. Electron candidates must have $p_T > 15 \text{ GeV}$ and are required to pass the 'tight' identification criteria described in Ref. [29]. To ensure isolation, the width of the cluster energy is required to be less than 0.3 around the electron candidate, not including the energy from the cluster associated to the candidate itself.

4. Event selection

At least one single electron or muon trigger is required for the event selection. A minimum of one reconstructed vertex, with at least three tracks associated with it, is required to remove non-collision backgrounds. The vertex with the largest sum of the $p_T^2$ computed from the associated tracks is selected as the primary vertex. Events with two leptons of the same flavour and opposite
charge with an invariant mass within 10 GeV of the Z boson mass are selected. For the $eeee$ and $\mu\mu\mu\mu$ channels more than one lepton pair combination may satisfy this criterion and the pair closest to the Z boson mass is chosen. This requirement of a lepton pair consistent with originating from a Z boson reduces much of the background from multijet and top-quark production, and a fraction of the diboson background.

Events are then required to have at least three reconstructed leptons originating from the primary vertex; their longitudinal impact parameters with respect to the primary vertex are required to be less than 10 mm.

The lepton not attributed to the Z boson decay must pass more stringent identification criteria than the leptons attributed to the Z boson, and have $p_T > 20$ GeV. Electrons are additionally required to pass the 'tight' identification criteria [29] with cuts on the matched track quality, the ratio of the energy measured in the calorimeter to the momentum of the matched track, and the detection of transition radiation. Segment-tagged muons may not be used as the third lepton.

Events are required to have $E_T^{miss} > 25$ GeV and the transverse mass of the $W^{\pm}$ boson candidate, $m_T^W$, formed from the $E_T^{miss}$ and the third lepton, is required to be greater than 20 GeV. These cuts suppress the remaining backgrounds from Z and ZZ production.

At least one of the leptons is required to have fired the trigger. To ensure that the trigger is well onto the efficiency plateau above the threshold of the primary single-lepton trigger, trigger-matched lepton-sampled events are required to have $p_T > 20$ GeV for muons and 25 GeV for electrons.

5. Signal efficiency and background estimate

The fiducial efficiency is defined as the ratio of simulated signal events meeting the event selection criteria to the numbers of simulated events within the defined fiducial phase space region. The values for each channel are shown in Table 1. The fraction of selected simulated signal events which come from outside the fiducial phase space is 13%.

The total systematic uncertainty on the efficiency is 3–7% depending on the decay channel and is dominated by the uncertainties on the electron and muon reconstruction. These include uncertainties associated with the reconstruction and identification efficiencies, energy scale, and isolation. The uncertainties are determined by comparing simulated events with data in control regions and are 2–6% depending on the decay channel. The uncertainties on the objects involved in the $E_T^{miss}$ calculation are used to derive the systematic uncertainties on $E_T^{miss}$ following Ref. [30]. Uncertainties in the description of the pile-up conditions by the simulation are also considered. The total systematic uncertainty on the acceptance of the $E_T^{miss}$ and transverse mass cuts due to the imperfect simulation is 1–2%.

Data-driven methods are used to estimate the backgrounds from $Z +$ jets and top-quark production. Simulation is used for the remaining background sources, including $W/Z + \gamma$ events where the photon converts into an electron–positron pair. The backgrounds from $W^+ + W^-$ and multijet production are negligible. For simulated events, the uncertainties on the theoretical cross section of the background processes are included in the systematic uncertainty.

In the $\mu\mu\mu\mu$, $eeee$ and $\mu\mu\mu\mu$ channels, the top-quark background contribution is evaluated from the average density of events in the side-bands around the Z mass peak after applying all selection cuts except the Z boson mass cut. Since the background from top-quark production does not contain a Z boson, this density is used to estimate the background from top-quark production in the signal region within the Z mass window. The systematic uncertainty is estimated from various cross checks, including a comparison of the difference between the side-band estimate and the prediction within the Z mass window in simulated events. This method is not applicable to the $eeee$ channel, since the Z + jet background dominates the side-bands due to electron misidentification, therefore a simulated event sample is used.

In order to estimate the background from $Z +$ jets events, a sample of events containing a Z boson candidate selected as described above and one "lepton-like" jet is identified. The lepton-like jet is a lepton candidate which does not explicitly have to satisfy lepton quality ($e$) or isolation ($\mu$) requirements. To ensure that the control sample is as similar to the signal as possible, all other event selection criteria, including the $E_T^{miss}$ and $m_T^W$ requirements, are applied. The background contribution is then estimated by scaling each event in the resulting sample by the probability $f(p_T)$ that a "lepton-like" jet satisfies the quality or isolation requirements. The scaling factor $f(p_T)$ is determined from a data sample of events containing a Z boson plus an extra lepton-like jet, with a low missing transverse momentum, $E_T^{miss} < 25$ GeV. The validity of extrapolation to high values of $E_T^{miss}$ has been verified with dijet events from simulation and data. An estimate of the systematic uncertainty is derived from the $E_T^{miss}$ extrapolation in dijet data.

6. Results

The numbers of expected and observed events after the full selection are shown in Table 2. A total of 71 $W^{\pm}Z$ candidates are observed in data, with $12.1 \pm 1.4$(stat.$)^{+7.3}_{-9.2}$(syst.) expected background events. The expected signal events shown in the table include the contribution from $\tau$ lepton decays into electrons or muons. The discrepancy between channels in the number of observed to expected events is consistent with a statistical fluctuation at the 16% level. The invariant mass and the transverse momentum of the Z boson in $W^{\pm}Z$ candidate events are shown in Figs. 1 and 2, respectively.

The fiducial cross section is calculated from

$$\sigma_{WZ \to \ell\ell\ell\ell}^{fid} = \frac{N_{obs}^{WZ \to \ell\ell\ell\ell} - N_{bkg}^{WZ \to \ell\ell\ell\ell}}{\mathcal{L} \times C_{WZ \to \ell\ell\ell\ell}} \times \left(1 - \frac{N_{MC}^{WZ \to \ell\ell\ell\ell}}{N_{MC}^{WZ \to \ell\ell\ell\ell}}\right) \times \left(\frac{1 - N_{MC}^{V} - N_{MC}^{WW} - N_{MC}^{ZZ}}{1 - N_{MC}^{WZ \to \ell\ell\ell\ell}}\right)$$  \hspace{1cm} (1)$$

where $N_{obs}^{WZ \to \ell\ell\ell\ell}$ and $N_{bkg}^{WZ \to \ell\ell\ell\ell}$ are the numbers of observed and background events, $\mathcal{L}$ the integrated luminosity and $C_{WZ \to \ell\ell\ell\ell}$ is the fiducial efficiency defined above. The last term corrects for the $\tau$ lepton contribution estimated from the selected simulated signal sample, where $N_{MC}^{WZ \to \ell\ell\ell\ell}$ is the number of $W^{\pm}Z$ events with at least one of the bosons decaying to a $\tau$ lepton and $N_{MC}^{WZ \to \ell\ell\ell\ell}$ is the number of $W^{\pm}Z$ events with decays into any lepton flavour. For each final state, the simulated signal samples include W and Z bosons.

Table 1

<table>
<thead>
<tr>
<th>Final state</th>
<th>$eeee$</th>
<th>$ee\mu + E_T^{miss}$</th>
<th>$e\mu\mu + E_T^{miss}$</th>
<th>$\mu\mu\mu + E_T^{miss}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial efficiency (%)</td>
<td>34.3 ± 0.8</td>
<td>50.2 ± 0.9</td>
<td>54.5 ± 1.0</td>
<td>81.6 ± 1.3</td>
</tr>
</tbody>
</table>

4 Contributions from $\tau$ lepton decays are excluded.
decaying into τ leptons. The contribution from τ lepton decays is 3.7% summing over all channels.

The total cross section is calculated as

$$\sigma_{\text{WZ}}^{\text{tot}} = \frac{\sigma_{\text{fid}}^{\text{WZ} \rightarrow \ell \ell \ell}}{B(\text{WZ} \rightarrow \ell \ell \ell) \times A_{\text{WZ} \rightarrow \ell \ell \ell}}$$

(2)

where $B(\text{WZ} \rightarrow \ell \ell \ell)$ is the branching ratio for a $W^\pm Z$ boson to decay to $\ell \ell$ and a $Z$ boson to decay to $\ell \ell$, and $A_{\text{WZ} \rightarrow \ell \ell \ell}$ is the ratio of the number of events within the fiducial phase space region to the number of events within $66 \text{ GeV} < m_{\ell \ell} < 116 \text{ GeV}$. This ratio $A_{\text{WZ} \rightarrow \ell \ell \ell}$ is calculated at NLO to be $0.342 \pm 0.006$ using MCFM [18] with PDF set CTEQ6.6, where the uncertainty arises from the statistical error due to the sample size in the MCFM integration (0.6%) and parton distribution function uncertainty (1.5%).

The cross section is determined by minimizing a negative log-likelihood function to combine the four channels. Systematic uncertainties are included as Gaussian-constrained nuisance parameters. For each systematic uncertainty, correlations between signal and background predictions are taken into account. All uncertainties are allowed to vary simultaneously in the fit.

The measurements of the combined fiducial cross section for the $W^\pm Z$ bosons decaying directly into electrons and muons, and the total inclusive cross section, are

$$\sigma_{\text{WZ} \rightarrow \ell \ell \ell}^{\text{ fid}} = 102^{+15}_{-14}\text{(stat.)}^{+7}_{-8}\text{(syst.)}^{+4}_{-4}\text{(lumi.)} \text{ fb},$$

(3)

$$\sigma_{\text{WZ}}^{\text{tot}} = 20.5^{+3.4}_{-2.3}\text{(stat.)}^{+1.4}_{-1.3}\text{(syst.)}^{+0.9}_{-0.8}\text{(lumi.)} \text{ pb},$$

(4)

The latter can be compared with the SM expectation, $17.3^{+1.3}_{-0.8} \text{ pb}$, calculated with MCFM [18].

In order to set limits on the anomalous coupling parameters, a frequentist approach [31] is used with the profile likelihood ratio used as the test statistic. The limits are set separately on each parameter with the other couplings fixed to their SM values. A reweighting procedure is used to predict the numbers of expected events as functions of the parameter being studied. The uncertainties on the signal acceptance and efficiency and on the background estimates are included as nuisance parameters with Gaussian constraints in the likelihood function. The 95% confidence interval (C.I.) is defined as the range(s) of the coupling parameter(s) for which at least 5% of randomly generated pseudo-experiments result in a smaller value of the profile likelihood ratio than is observed with the data.

The observed and expected 95% C.I. for the anomalous couplings are summarized in Table 3. The observed limits are compared with DØ results from $W^\pm Z$ production in Fig. 3. Other results on anomalous couplings from $W^+ W^-$ production can be found in Refs. [32–38]. Significant improvements in these limits are expected with more integrated luminosity and refined extraction methods which take advantage of the differential spectra of kinematic quantities. The anomalous couplings influence the kinematic properties of $W^\pm Z$ events and thus the fiducial efficiency. The $C_{WZ}$ variation within the measured aTGC limits results maximally in a 3% decrease of the fiducial cross section.
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References


Table 3

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Observed ((\Lambda = 2) TeV)</th>
<th>Observed ((\Lambda = \infty))</th>
<th>Expected ((\Lambda = \infty))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta g_1^Z)</td>
<td>[-0.20, 0.30]</td>
<td>[-0.16, 0.24]</td>
<td>[-0.12, 0.20]</td>
</tr>
<tr>
<td>(\Delta \kappa_2)</td>
<td>[-0.9, 1.1]</td>
<td>[-0.8, 1.0]</td>
<td>[-0.6, 0.8]</td>
</tr>
<tr>
<td>(\lambda_2)</td>
<td>[-0.17, 0.17]</td>
<td>[-0.14, 0.14]</td>
<td>[-0.11, 0.11]</td>
</tr>
</tbody>
</table>

7. Conclusion

A measurement of the \(W^\pm Z\) production cross section has been performed using final states with electrons and muons, in LHC pp collisions at \(\sqrt{s} = 7\) TeV with ATLAS. In data with an integrated luminosity of 1.02 fb\(^{-1}\), a total of 71 candidates is observed with a background expectation of 12.1 \(\pm 1.4\) (stat.) \(\pm 1.3\) (syst.) events. The SM expectation for the number of signal events is 50.3 \(\pm 4.4\) (stat.) \(\pm 4.3\) (syst.). The fiducial and total cross sections determined in the present work are given in Eqs. (3) and (4), respectively. The total cross section is in good agreement with the SM expectation. Limits on the anomalous triple gauge couplings \(\Delta g_1^Z\), \(\Delta \kappa_2\) and \(\lambda_2\) are reported and the results are consistent with zero, as expected from the SM.

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