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# Measurement of the $W^+W^- \to \ell\nu\ell\nu$ production cross-section at $\sqrt{s} = 8$ TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS Detector

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The production of opposite-charge $W$-boson pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV and 13 TeV is measured using data corresponding respectively to 20.3 fb$^{-1}$ and 3.16 fb$^{-1}$ of integrated luminosity collected by the ATLAS detector during 2011-2012 and 2015 at the CERN Large Hadron Collider. The $WW$ pairs are reconstructed using their leptonic decays into an electron and a muon and neutrinos and no hadronic jets. An extension of the measurement is presented, which covers also the $WW+1$ jet production at 8 TeV. The cross-section measurement is performed in a fiducial phase space close to the experimental acceptance and is compared to theoretical predictions. The integrated measurement is corrected for all acceptance effects in order to obtain the total $WW$ production cross-section. Agreement is found between the measurement and the highest order QCD calculations available. Fiducial differential cross-sections are measured as a function of kinematic variables and limits on anomalous triple-gauge-boson couplings are reported.

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## 1. Introduction

The measurement of the production of opposite-charge $W$-boson pairs ($WW$) is an important test of the non-Abelian gauge structure of the electroweak theory of the Standard Model (SM). The $WW$ signal is composed of three leading sub-processes, which are $q\bar{q} \to WW$ production (in the $t$- and $s$-channels), the non-resonant $gg \to WW$ production and the resonant $gg \to H \to WW$ production (both $gg$-initiated processes occurring through a quark loop). These sub-processes are known theoretically at different orders in the strong coupling constant $\alpha_s$. At the Large Hadron Collider (LHC), the $WW$ production cross-sections have been measured for centre-of-mass energies of $\sqrt{s} = 7$, 8 and 13 by the ATLAS [1, 2, 3] and CMS [4, 5] collaborations. Significant progress has been made in theoretical calculations to include higher-order corrections in perturbative Quantum Chromodynamics (pQCD), in order to match the experimental precision and address discrepancies between data and theory reported in some of the 8 TeV results.

The total and fiducial $WW$ production cross-sections are measured using their leptonic decays into an electron and a muon and neutrinos. Events with reconstructed jets are not included in the candidate event sample. The results are presented using a data sample with an integrated luminosity of 20.3 fb$^{-1}$ at a centre-of-mass energy of $\sqrt{s} = 8$ TeV collected by the ATLAS detector [6]. Furthermore, measurements of differential cross-sections are presented and limits on anomalous triple-gauge-boson couplings are reported.

An extension of the measurement is presented, which covers also the $WW + 1$ jet production at 8 TeV [7]. Only events with exactly one reconstructed jet are selected. The cross-section of $WW + 1$-jet production is extracted for the fiducial phase-space region. The results are combined with the previous measurement, restricted to final states without any reconstructed jets. The fiducial $WW + 1$-jet cross-section and the ratio $R_1$ of the fiducial $WW + 1$-jet and fiducial $WW + 0$-jet cross-sections is determined and compared to different theoretical predictions.

The $WW$ cross-section is also measured at $\sqrt{s} = 13$ TeV using an integrated luminosity of 3.16 fb$^{-1}$ within a fiducial phase space close to the geometric and kinematic acceptance of the experimental analysis. The ratio of cross-sections at 13 TeV and 8 TeV centre-of-mass energies in the respective fiducial phase spaces is presented. Both measurements are compared to the latest theoretical predictions.

## 2. $WW$ selection

For the 8 TeV analysis, the $WW$ candidate events are required to contain two oppositely isolated charged leptons with transverse momenta $p_T^\ell > 25$ GeV and $p_T^\ell > 20$ GeV. Events with additional leptons with $p_T^\ell > 7$ GeV are rejected, which helps to suppress other diboson processes with more than two leptons. The invariant mass of the dilepton pair is required to be greater than 15 GeV for $ee/\mu\mu$ to reject $J/\psi$, $\Upsilon$ and other low mass resonances, while $e\mu$ final states are required to have an invariant mass above 10 GeV to remove multijet events. The Drell–Yan production is the largest background for the $ee$ and $\mu\mu$ final states, and it is reduced by rejecting events that are reconstructed with an invariant mass closer than 15 GeV to the $Z$ boson mass. More stringent cuts are applied to further suppress the Drell–Yan background. The relative missing transverse momentum, $E_{\mathrm{T,Rel}}^{\mathrm{miss}}$ is defined as the missing transverse momentum component perpendicular to the direction in the $r-\phi$ plane of the lepton closest to the $E_{\mathrm{T}}^{\mathrm{miss}}$ direction, and is required to be larger than 15 GeV for the $e\mu$ and larger than 45 GeV for the $ee/\mu\mu$ final states. Track-based missing transverse momentum, $p_{\mathrm{T}}^{\mathrm{miss}}$ is further required to be larger than 20 GeV for the $e\mu$ and larger than 45 GeV for the $ee/\mu\mu$ final states. The azimuthal angle between $E_{\mathrm{T,Rel}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{\mathrm{miss}}$ is calculated and the condition $\Delta\phi(E_{\mathrm{T,Rel}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.6$ must be fulfilled in the $e\mu$ final state, while $\Delta\phi(E_{\mathrm{T,Rel}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.3$ must be satisfied for the $ee$ and $\mu\mu$ final states. In order to suppress the dominant top-quark background, events are required to contain no selected jets with $p_T > 25$ GeV in $|\eta| < 4.5$. This selection is referred to as $WW + 0$-jet final state.

For the $WW + 1$-jet 8 TeV analysis, the selection follows closely the one above to facilitate the combination with the $WW + 0$-jet final state. Only final states with one electron, one muon and exactly one jet are selected. To reduce the background from top-quark production, events containing $b$-jets with $p_T > 20$ GeV and within $|\eta| < 2.5$ are rejected.

Similarly, the $WW + 0$-jet 13 TeV analysis is restricted to $e\mu$ final state and the leptons are required to have $p_T^{\ell} > 25$ GeV. To suppress the background contribution from top quarks, events are required to have no jets with $p_T > 25(30)$ GeV in $|\eta| < 2.5(4.5)$ and no $b$-jets with $p_T > 20$ GeV. In addition, the requirements $E_{\mathrm{T,Rel}}^{\mathrm{miss}} > 15$ GeV, $p_T^{\mathrm{miss}} > 20$ GeV and the invariant mass of the lepton pair $m_{e\mu} > 10$ GeV suppress Drell–Yan background contributions.

Backgrounds stemming from top-quark, Drell–Yan, $W$+jets and multijet production are evaluated using data-driven methods. The background from diboson production processes is modelled using MC samples normalized to the expected production cross section using theoretical calculations at the highest available orders.

## 3. $WW + 0$-jet results at $\sqrt{s} = 8$ TeV

The measurement is conducted in three dilepton final states ($e\mu, \mu\mu$, and $ee$) that are all accompanied by missing transverse momentum. Fiducial and total cross-sections are measured. The uncertainty of the fiducial cross-section measurement is dominated by systematic uncertainties due to reconstruction and background estimation. The fiducial cross-sections for the three final states are about two standard deviations higher than the partial next-to-leading (NLO) predictions. However, the difference is reduced by taking into account higher-order effects that increase the cross-section prediction by 5-10%. The measured fiducial cross-sections are found to be consistent with predictions that include both the next-to-next-to-leading order (NNLO) and resummed QCD corrections up to next-to-next-to-leading logarithms (NNLL) accuracy. A graphical comparison between the fiducial cross-section measurement in $e\mu$ final state and various theoretical predictions is shown in figure 2. The measured total $WW$ production cross-section is measured to be $71.1 \pm 1.1(\mathrm{stat})^{+5.7}_{-5.0}(\mathrm{syst}) \pm 1.4(\mathrm{lumi})$ pb [2], from the combination of the three analysed final states extrapolated to the full phase space. This is about 1.4 standard deviations higher than the NNLO prediction of $63.2^{+1.6}_{-1.4}(\mathrm{scale}) \pm 1.2(\mathrm{PDF})$ pb [2]. Differential cross-sections are measured in the fiducial region using events in the $e\mu$ final state.The shapes of the measured unfolded differential cross-section distributions agree with the predictions at the level of 15%, and the discrepancy is mainly caused by the overall normalization offset as shown in figure 1.

The distribution of the transverse momentum of the leading lepton, $p_{\mathrm{T}}^{\mathrm{lead}}$, is used to investigate anomalous triple-gauge-boson coupling (aTGC) parameters. The data show no indication of anomalous couplings and are fully compatible with the SM, thus limits on these parameters are derived. Figure 1 compares the detector-level $p_T^{\text{lead}}$ distribution with the SM prediction as well as the predictions for non-zero aTGC parameters, which are defined in the no constraints scenario that assumes no correlation between the parameters. The predicted shapes shown in figure 1 are the values of aTGC parameters corresponding to the upper bounds of the observed 95% confidence interval. The limits are better than expected due to a deficit in data for large $p_T^{\text{lead}}$. Due to the increased integrated luminosity and the higher centre-of-mass energy, the limits reported here in figure 1 are more stringent than those previously published by the ATLAS Collaboration using data taken at $\sqrt{s} = 7$ TeV [1]. They are also competitive with the results obtained at the LEP collider [8].

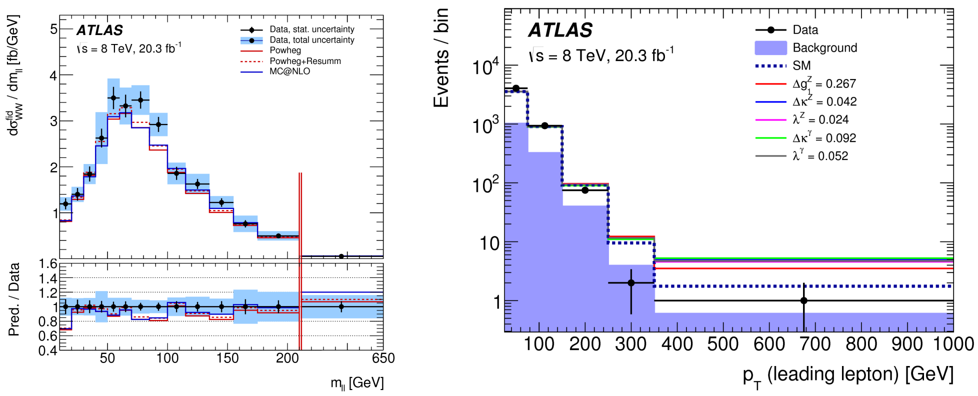


**Figure 1:** Measured unfolded differential cross-sections of $WW$ production in the $e\mu$ final state for the invariant mass $m_{\ell\ell}$ of the dilepton system (left). The leading lepton transverse momentum, $p_T^{\text{lead}}$ for the $e\mu$ final state is compared for data and Monte Carlo generated events using values of anomalous triple-gauge-boson coupling parameters corresponding to the upper bounds of the observed 95% confidence interval (right) [2].

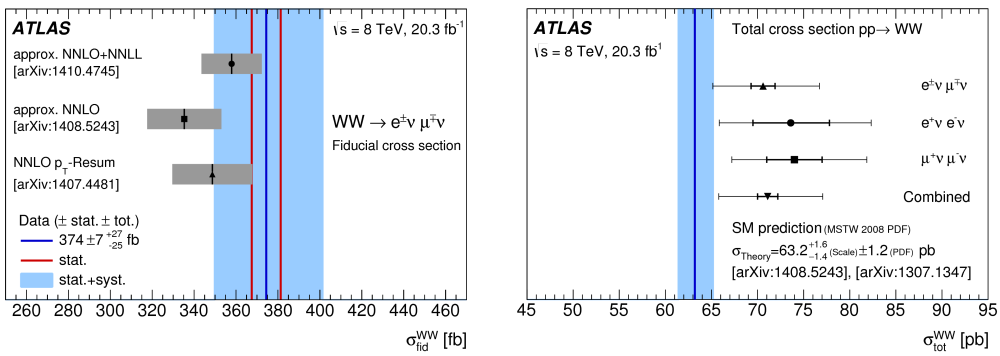


**Figure 2:** Comparison of the measured fiducial cross-sections with various theoretical predictions (left). The measured $WW$ total cross-sections compared to the NNLO prediction (right) [2].

## 4. $WW + 1$-jet results at $\sqrt{s} = 8$ TeV

Only events with exactly one reconstructed jet are selected for this measurement. The fiducial

$WW+1$-jet cross-section is measured to be $136 \pm 16$ fb [7] within the fiducial volume defined by the kinematic requirements placed in the analysis. It is found to be in very good agreement with the theoretical prediction obtained by combining the total cross-section calculations of $q\bar{q} \to WW$ at $O(\alpha_s^2)$, non-resonant $gg \to WW$ at $O(\alpha_s^3)$ and the resonant $gg \to H \to WW$ at $O(\alpha_s^4)$ and multiplying them with their respective acceptance factor $A_{WW}$. The measured fiducial $WW+ \leq 1$-jet cross-section of $511 \pm 29$ fb [7] agrees within the uncertainty with the prediction. A comparison of the measured and predicted fiducial cross-sections is given in figure 3. Uncertainties causing migrations of events between jet bins are significantly reduced when comparing the fiducial $WW+0$-jet cross-section and the $WW+ \leq 1$-jet cross-section. The previously dominant experimental uncertainty in the jet energy scale is reduced by a factor of 2.5 by extending the measurement to include 1-jet final states. Additional uncertainties introduced by the rejection of $b$-jets and increased uncertainties in the estimation sof background contributions cause the overall experimental uncertainty to be lower by only 18%.

The ratio of jet-binned fiducial cross-sections $R_1$, defined as $R_1 = \frac{\sigma_{\mathrm{WW}}^{\mathrm{fid.,1-jet}}}{\sigma_{\mathrm{WW}}^{\mathrm{fid.,0-jet}}}$ is determined to be $0.36 \pm 0.05$ and compared to various theoretical predictions, which are all found to agree with the measurement within the uncertainties as illustrated in figure 3.

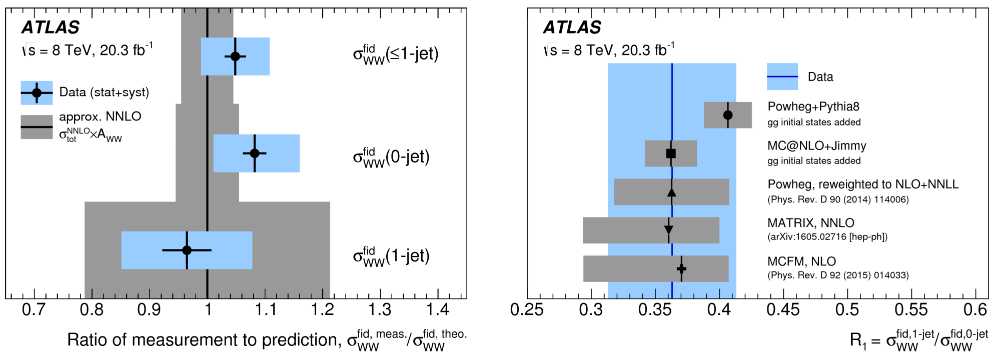


**Figure 3:** Comparison of the measured cross-sections in the 0-jet, 1-jet and $\leq 1$-jet fiducial regions. The ratio of the measured cross-sections to their respective theoretical prediction is shown (left). Jet-binned fiducial cross-section ratio $R_1$ measured in data and compared to theoretical predictions is shown (right) [7].

## 5. $WW+0$-jet results at $\sqrt{s} = 13$ TeV

The production cross-section of the $WW$ pairs at $\sqrt{s} = 13$ TeV is measured in a fiducial phase space of the $e\mu$ final state in which events with reconstructed jets are excluded. The data used in the analysis correspond to an integrated luminosity of 3.16 fb$^{-1}$. The measurement is made in a relatively pure signal region with the contamination from the dominant background processes estimated using data in dedicated control regions. The measured cross-section is $529 \pm 20(\mathrm{stat}) \pm 50(\mathrm{syst}) \pm 11(\mathrm{lumi})$ fb [3] and is found to be consistent with the most up-to-date SM predictions that include high-order QCD effects, taking into account systematic uncertainties associated to the selection of the fiducial phase space as shown in figure 4. The total uncertainty is dominated by systematic effects, of which the largest contribution originates from the experimental jet selection and calibration. Furthermore, the ratio of the measured fiducial cross-sections at 13 and 8 TeV centre-of-mass energies is compared to the theory predictions with reduced uncertainties, thanks to their cancellation in the ratio. These results show that high-order QCD calculations describe the data well as illustrated in figure 4.

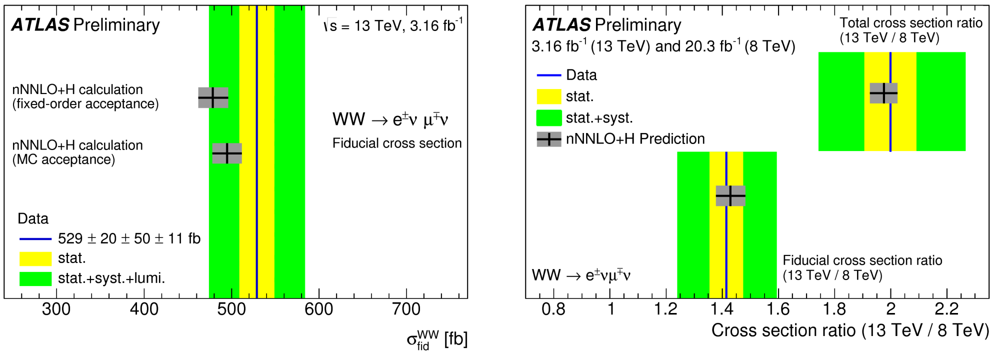


**Figure 4:** The measured fiducial cross-section in comparison with the predictions in the fiducial phase space with two different acceptance calculations (left). Measurements of the ratios of cross-sections at the two centre-of-mass energies of 13 and 8 TeV in the fiducial and total phase spaces (right) [3].

## References


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