PROCEEDINGS OF SCIENCE

Measurement of the diboson production cross section at 8TeV and 13TeV and limits on anomalous triple gauge couplings with the ATLAS detector

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Diboson measurements allow to test the gauge structure of the Standard Model, verify the validity of Standard Model theory predictions and probe new physics beyond the reach of the LHC in a model-independent way via anomalous triple gauge couplings (aTGC).
Measurements on WW, WZ, and ZZ diboson production, differential cross sections and aTGC limits obtained with these channels, have been published, using ATLAS data at center-of-mass energies of $\sqrt{s}$ =8 TeV and 13 TeV collected in 2012, 2015 and 2016. In the following, a short summary of these diboson measurements focusing on recent results will be given.

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1. W^+W^- cross section measurements

Production cross section of W^+W^- at a center-of-mass energy of $\sqrt{s} = 8$ TeV [1] and a total integrated luminosity $\mathscr{L} = 20.3$ fb^{-1} of ATLAS [2] data is measured using fully leptonic states. Only electrons, denoted e in the following, and muons μ are selected, giving rise to three possible lepton combinations: ee, $\mu\mu$ and $e\mu$. The challenge of this measurement is the large $t\bar{t}$ background which has the same signature as the signal plus additional jets. A jet-veto on any jet in the event with $p_T > 25$ GeV has been applied in order to reject most of the $t\bar{t}$ background ($\sigma_{WW}^{0\,jet}$). The uncertainty on the fiducial cross section $\sigma_{\rm fid}$ is dominated by reconstruction uncertainties, mainly the jet energy scale, and background estimation uncertainties. The modeling of the extrapolation of the fiducial cross section to the total cross section is the dominant uncertainty on the total cross section $\sigma_{\rm tot}$. A deviation of 2σ is found comparing $\sigma_{\rm fid}$ with its NLO theory prediction and 1.4σ comparing the $\sigma_{\rm tot}$ measurement with its theory predictions at approximated NNLO[1]. Missing higher-order calculation are assumed to be the reason of this discrepancy.

Differential cross sections for a few kinematic distributions are measured in the $WW \rightarrow e\nu\mu\nu$ channel and compared to NLO theory predictions. The shapes of the differential distributions are generally very well described by NLO predictions. As it has been observed that NLO predictions are lower than NNLO predictions, the discrepancy in the normalization is assumed to be due to a modeling effect.

On the theory side, efforts have been made to extend the theory prediction to include higher orders in gluon-gluon fusion and also resonant WW production via a decaying Higgs to order $\mathscr{O}(\alpha_s^4)$. Furthermore, fully differential predictions at NNLO [3] and also NLO predictions on WW production with up to three jets [4] [5] have become available. It is therefore interesting to extend the measurement phase space and also measure WW production in association with one jet ($\sigma_{WW}^{1\,jet}$) [6] and to combine these results to obtain the production cross section $\sigma_{WW}^{\leq 1\,\rm jet}$ in order to reduce the theory uncertainty and to compare the newly available predictions with data. In the W^+W^-+1jet channel, only decays to $e\nu\mu\nu$ are selected where the lowest background and highest signal acceptance is expected. Event selection for both measurements are similar to ease the combination of the two measurements.

The systematic uncertainty of the combined cross section $\sigma_{WW}^{\leq 1\,\rm jet}$ is 5.1%. The total precision of the measurement is increased by 12% compared to the measurement of only $\sigma_{WW}^{0\,jet}$ due to the combination. The resulting cross sections are in very good agreement with the approximated NNLO theory prediction as can be seen in Figure 1, left.

Using 2015 ATLAS data at a center-of-mass energy of $\sqrt{s} = 13$ TeV, the WW+0jet cross section in the $WW \rightarrow e\nu\mu\nu$ channel was measured [7]. Measurement approach and selection are very similar to the measurements at $\sqrt{s} = 8$ TeV. Fiducial cross section results and the cross section ratio $\frac{\sigma_{WW}^{13TeV}}{\sigma_{WW}^{8TeV}}$, using the cross section results on $\sigma_{WW}^{0\,jet}$ in the $WW \rightarrow e\nu\mu\nu$ channel for different center-of-mass energies, are in good agreement with theory predictions as shown in Figure 1, right. The measurement precision on the fiducial cross section is 11%.

[1] Approximated NNLO predictions for the fiducial cross section were obtained using the NNLO theory predictions for the total cross section and the predictions on the detector acceptance at NLO.

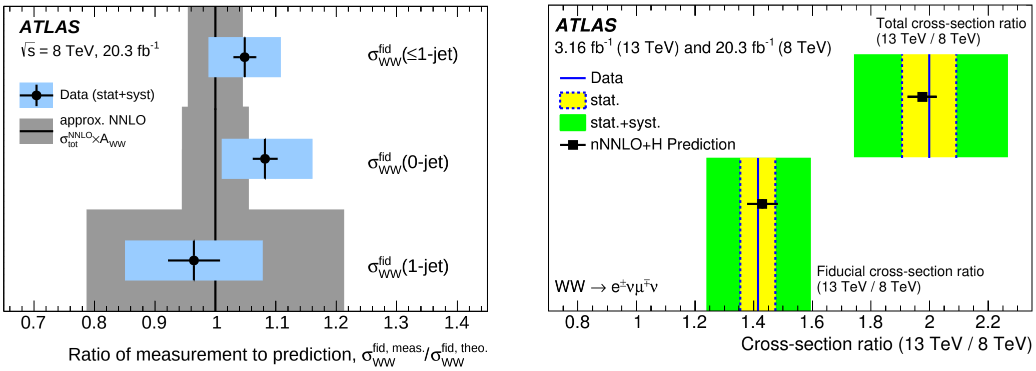

Figure 1: WW cross section results for WW production in association with zero and one jet and their combination in comparison with theory [6] (left) and the cross section ratio $\frac{\sigma_{WW}^{13TeV}}{\sigma_{WW}^{8TeV}}$ in comparison with its approximated NNLO theory prediction [7] (right).

2. WZ cross section measurements

Cross section of WZ diboson production were measured using the leptonic decay of both W and Z boson with a final state of three leptons and missing transverse energy. Only electrons and muons were taken into account. The measurement uses the full 2012 dataset with $\mathscr{L} = 20.3$ fb^{-1} at $\sqrt{s} = 8$ TeV [8] and is up to now the most precise measurement on the WZ fiducial cross section achieving a precision of 4.2%. Dominant uncertainties arise from the misidentified lepton background, statistics and the luminosity measurement uncertainty. Results on the fiducial and total cross section are slightly above the corresponding theory predictions at NLO, the discrepancy is assumed to be due to missing higher-order corrections in the modeling of the theory prediction.
Cross-section measurements using the fully leptonic decay of the WZ diboson pair are as well available for the full 2015 dataset at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of $\mathscr{L} = 3.2$ fb^{-1} [9]. The theory prediction on the fiducial cross section, available at NLO, underestimates the measured fiducial cross section, as for both measurements at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV. However, very recently, NNLO predictions on the total cross section have been published [10]. A comparison of the extrapolated measured total cross section and the NNLO prediction on the total cross section shows a good agreement as shown in Figure 2. The differential cross section of the jet multiplicity N_{jets} was measured and found to be in better agreement with the prediction of the SHERPA Monte-Carlo event generator than with the one of POWHEG+PYTHIA.
The cross section measurement was repeated with larger statistics using the full 2015 and a part of the 2016 dataset with a total luminosity of $\mathscr{L} = 13.3$fb^{-1} at $\sqrt{s} = 13$ TeV [11]. Differential cross sections are extracted for the WZ transverse mass m_{T}^{WZ} and the transverse momentum of the Z boson p_{T}^{Z}. Both results are in good agreement with POWHEG+PYTHIA and SHERPA predictions.

3. ZZ cross section measurements

Cross sections of ZZ diboson production were measured using Z boson decays to either a pair of electrons, muons (denoted leptons ℓ) or neutrinos. At $\sqrt{s} = 8$ TeV, using the full dataset

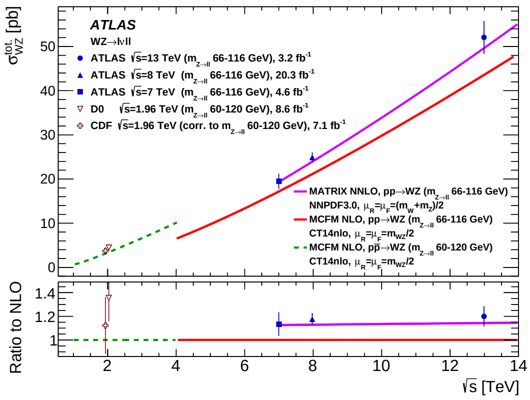

Figure 2: Measured WZ total cross sections at $\sqrt{s}$ =7, 8 and 13 TeV compared to NLO (red) and NNLO theory predictions (purple) [9].

available of $\mathscr{L} = 20.3$ fb^{-1}, the ZZ decay channels $ZZ \to \ell\ell\ell'\ell'$ (4ℓ) and $ZZ \to \ell\ell\nu\nu$ ($2\ell2\nu$) were considered [12]. The two Z bosons are required to be on-shell with $66 < m_{\ell\ell} < 116$ GeV for the 4ℓ channel and $76 < m_{\ell\ell} < 106$ GeV for the $2\ell2\nu$ channel where $m_{\ell\ell}$ is the invariant mass of the charged lepton pair associated with a Z boson.
Fiducial cross sections are extracted separately for each channel and lepton combination, combined and extrapolated to the total Phase-Space (σ^{total}) for on-shell Z-bosons as shown in Figure 3, left, with a precision on the total cross section of 8%. The combined total cross section and the fiducial cross sections are compatible with theory predictions at NLO.
Differential cross sections were measured separately in the 4ℓ and $2\ell2\nu$ channels for several kinematic and angular distributions and the jet multiplicity. In the 4ℓ channel, all measurements are consistent within 1σ with the Standard Model (SM) in most bins. In the $2\ell2\nu$ channel, the results are consistent with the SM within 1-2σ.
Cross section measurements are also done at a center-of-mass energy of $\sqrt{s}$ =13 TeV using an integrated luminosity of $\mathscr{L} = 3.2$ fb^{-1} in the 4ℓ channel [13]. The results agree well with the Standard Model theory predictions at NNLO as shown in Figure 3, right.

4. Limits on anomalous triple gauge couplings

Using the above-described diboson production measurements, limits on anomalous triple gauge couplings (aTGCs) were derived. To parameterize aTCG, two different theoretical frameworks are used: the Effective Lagrangian [14] and the Effective field theory (EFT) approach [15]. Both parametrizations are equivalent and can be converted one into another. In the EFT parameterization, the aTGC parameters are zero in the SM. No indications for aTGCs were found and limits were derived.
Limits on charged aTGC, derived from the WZ and WW production measurements, are provided using both parameterizations. Limits on neutral aTGC, evaluated using measured ZZ diboson event yields, are given in the vertex function approach, an Effective Lagrangian approach [16].
Charged aTGC probe the WWZ and the $WW\gamma$ vertices. Observables which depend on the center-

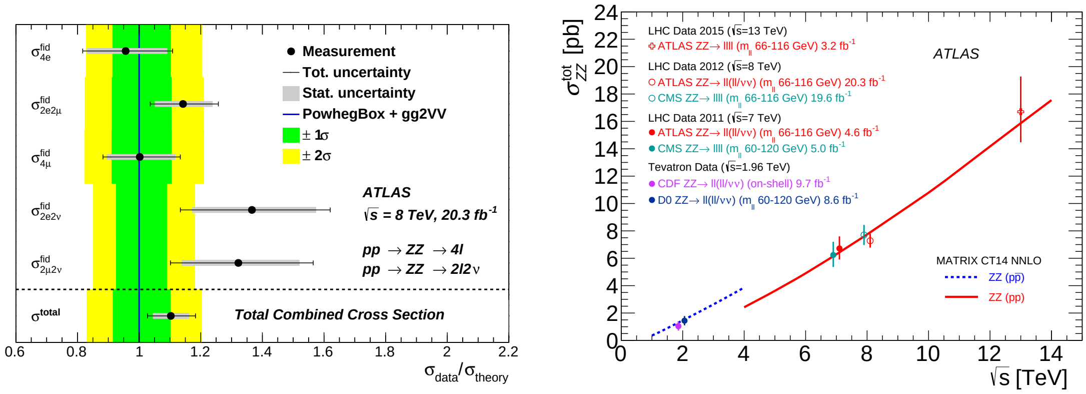

Figure 3: Fiducial cross section of ZZ production in the 4ℓ and $2\ell 2\nu$ channels and their combination for $\sqrt{s} = 8$ TeV [12] (left) and the total ZZ cross section compared to its NNLO prediction [13] (right).

of-mass energy of the colliding partons are sensitive to aTGC: in case of non-zero aTGCs, their event yield will increase at high partonic center-of-mass energies. The distribution of the transverse mass of the WZ system, m_{T}^{WZ} is used to extract limits on aTGC in the WZ analysis and the transverse momentum distribution of the leading lepton $p_{\mathrm{T}}^{\mathrm{lead}}$ is used for WW. The event yield at high values of these variables is enhanced by the presence of aTGC. Limits the EFT parameterization obtained with the WZ and the WW analyses are listed in Table 1. For the limits obtained with WZ events, both $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV data were used and the combination improves previous limits obtained using $\sqrt{s} = 8$ TeV data alone by a factor of 1.3. Limits on aTGC from WW events were derived using the WW+0jet measurement at $\sqrt{s} = 8$ TeV and are more stringent than previous limit results by ATLAS at $\sqrt{s} = 7$ TeV by up to 50%. Comparing the limits for WZ and WW, limits obtained using WW events for the parameter c_B are more stringent than the limits from WZ events. WW is more sensitive to this parameter as the WW diboson pair can also be produced involving a photon. The WZ measurement gives stricter limits on the parameters c_W and c_{WWW}.
Measurements of ZZ production at $\sqrt{s} = 8$ TeV are used to probe ZZZ and $ZZ\gamma$ vertices. These vertices are forbidden in the SM and the aTGC parameters are therefore zero in the absence of deviations from the SM. Limits on aTGCs are extracted separately from $ZZ \to 4\ell$ events, where the tail of the transverse momentum distribution of the leading Z boson, $p_{\mathrm{T}}^{Z,\mathrm{lead}}$ is used and from $ZZ \to 2\ell 2\nu$ events, where the tail of the transverse momentum distribution of the Z decaying to charged leptons is used. No indications for neutral aTGCs were found and limits were derived as listed in Table 2. These limits are more stringent than previous ATLAS results by a factor 4.

5. Conclusion

During the past year, diboson measurements of WW, WZ and ZZ with pure leptonic decays at 8 TeV center-of-mass energy have been published by the ATLAS Collaboration. New measurements exploiting the recent data at $\sqrt{s} = 13$ TeV recorded in 2015 and 2016, were also released. Generally, good agreement with NNLO theory prediction was observed and no hints for aTGC were found. Limits on aTGC were derived which are more stringent than previously obtained by

	WZ measurements		WW measurements	
Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]	Expected [TeV^{-2}]	Observed [TeV^{-2}]
c_W/Λ^2	[-3.4;6.9]	[-3.6;7.3]	[-12.58;14.32]	[-5.87;10.54]
c_B/Λ^2	[-221;166]	[-253;136]	[-35.8;38.4]	[-20.9;26.3]
c_{WWW}/Λ^2	[-3.2;3.0]	[-3.3;3.2]	[-7.62;7.38]	[-4.61;4.60]

Table 1: Limits on charged aTGC in the EFT framework obtained using WZ events [11] (left) and WW events [1] (right).

Coupling	Expected ($\times10^{-3}$)	Observed ($\times10^{-3}$)
f_4^γ	[-4.6;4.8]	[-3.8;3.8]
f_4^Z	[-4.0;4.1]	[-3.3;3.2]
f_5^γ	[-4.8;4.8]	[-3.8;3.8]
f_5^Z	[-4.1;4.1]	[-3.3;3.3]

Table 2: Limits on neutral aTGCs obtained in the Vertex function approach [12].

ATLAS. Future measurements on the larger $\sqrt{s} = 13$ TeV dataset will even further improve experimental precision.

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