PROCEEDINGS OF SCIENCE

Measurement of the $ZZ^{(*)}$ and $Z\gamma$ production cross sections at 8 TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector

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Measurements of the cross sections of the production of pairs of electroweak gauge bosons at the LHC constitute stringent tests of the electroweak sector of the Standard Model and provide a model-independent means to search for new physics at the TeV scale. The ATLAS collaboration has measured inclusive and differential cross sections of the production of ZZ pairs and Z and photon pairs, using final states with the Z decaying to charged leptons or neutrinos. First integrated measurements of the ZZ pair production cross sections using fully leptonic final states at 13 TeV using data corresponding to 3.2 /fb are presented. Detailed studies of integrated and differential cross sections have been performed using data corresponding to 20.3 /fb at a centre-of-mass energy of 8 TeV. The measurements are performed as a function of a variety of kinematic variables calculated from the leptons, like the transverse momentum or rapidity of the vector bosons. For the case of the production of four charged leptons a measurement of the four-lepton invariant mass spectrum ranging from 80 to 1000 GeV was performed, where several distinct physics processes give rise to the production of four-lepton final states. All measurements are compared to calculations at up to NNLO in pQCD. Constraints on new physics are provided by setting limits on anomalous triple couplings between neutral vector bosons, which are forbidden at tree level in the Standard Model.

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1. Introduction

This paper presents the ZZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV, the inclusive production of four isolated charged leptons at $\sqrt{s} = 8$ TeV, and the production of a Z boson associated with an isolated photon at $\sqrt{s} = 8$ TeV. All the analyses have been performed with the ATLAS detector [1].

2. Measurement of the ZZ Production Cross Section at $\sqrt{s} = 13$ TeV

This measurement presents the measurement of the ZZ production cross section in pp interactions at $\sqrt{s} = 13$ TeV [2]. The analyzed data correspond to an integrated luminosity of 3.2 ± 0.2 fb^{-1}.

The candidate events are reconstructed in the fully leptonic decay channel $ZZ \rightarrow l^+l^-l'^+l'^-$ where the final state leptons can be either an electron or a muon. The events are preselected by either a single-muon or dielectron trigger. The final state leptons must be prompt and isolated with $\Delta R_{l,l'} > 0.2$[1] in between all leptons. All selected leptons must have $p_T > 20$ GeV. If the lepton is an electron, it must have a pseudorapidity $|\eta| < 2.47$, while at least one muon in the 4μ channel must have a pseudorapidity $|\eta| < 2.4$. The remaining muons must satisfy $|\eta| < 2.7$.

The selected events must have exactly four leptons satisfying the above criteria forming two pairs of same-flavor oppositely charged leptons creating the three signal channels $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, and $e^+e^-\mu^+\mu^-$, termed $4e$, 4μ and $2e2\mu$ respectively, with $4l$ denoting all channels together. Each lepton pair must have an invariant mass in the range $66-116$ GeV. In the 4e and 4μ channels where there are two possible ways of forming same-flavor oppositely charged lepton pairs, the selected combination is the one that minimizes $|m_{ll,a} - m_Z| + |m_{ll,b} - m_Z|$ where $m_{ll,a}$ and $m_{ll,b}$ are the invariant masses of the two lepton pairs and m_Z is the mass of the Z boson [3].

A total of 63 events has been observed, 15 in the 4e, 30 in the $2e2\mu$ and 18 in the 4μ channels respectively.

The background for events with at least four prompt leptons in the final state are estimated with Monte Carlo samples. These are contributions from ZZ processes, where at least one Z boson decays to τ leptons, contributions from non-hadronic triboson processes and, last, contributions from $t\bar{t}Z$ processes are estimated with the use of Monte Carlo samples. Events from processes with two or three prompt leptons and hadronic activity in the event, can pass the event selection. This background contribution was estimated using control samples and a data-driven technique described in [4].

The measured fiducial[2] cross sections are shown in Table 1 and Figure 2 along with the comparison to the theoretical calculations [5].

Figure 2, left, shows the ratio of the fiducial cross sections for each channel and their combination, to the respective theoretical predictions. All measurements are in good agreement with the Standard Model (SM). On Figure 2, right, the measured total cross sections at different center-of-mass energies are compared to MCFM [6] with the CT14 NLO PDFs [7].

[1] $\Delta R_{l,l'} = \sqrt{(\Delta\eta_{l,l'}) + (\Delta\phi\eta_{l,l'})}$.

[2] The part of the phase space defined by the kinematical and geometrical requirements on the leptons; see [2].

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	Measurement	$\mathcal{O}(\alpha_s^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(\text{stat.})\ ^{+0.6}_{-0.4}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8\ ^{+1.8}_{-1.5}(\text{stat.})\ ^{+0.3}_{-0.3}(\text{syst.})\ ^{+0.4}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\ ^{+3.9}_{-3.6}(\text{stat.})\ ^{+1.0}_{-0.8}(\text{syst.})\ ^{+1.7}_{-1.3}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb

Table 1: Cross section measurements results compared to their theoretical Standard Model predictions. The experimental results are presented along with the statistical, systematic and luminosity uncertainties. Regarding the theoretical predictions, the PDF and renormalization and factorization scale uncertainties, added in quadrature, are shown. Taken from [2].

Figure 2 (left) also shows the total combined cross section. All measurements agree with the SM predictions. On the right of Figure 2 the measured total cross section is compared to measurements from lower center-of-mass energies and to a prediction from MCMFM [6] with the CT14 NLO PDFs [7] and is shown versus center-of-mass energy.

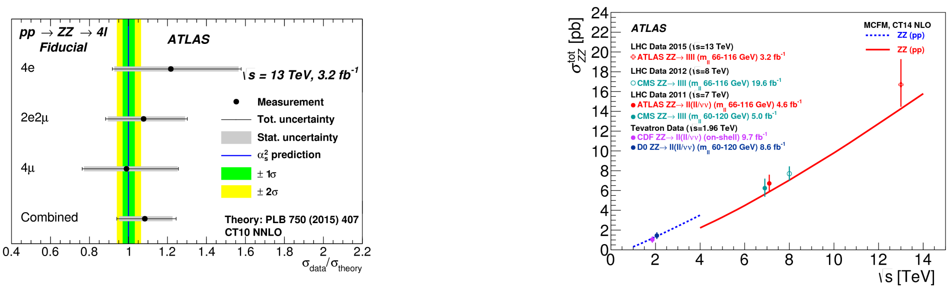

Figure 1: Left: Comparison between measured fiducial cross sections and their theoretical predictions. Right: Total cross section compared to measurement at lower center-of-mass energies by ATLAS, CMS, CDF and D0 and to a prediction from MCFM. Figures were taken from [2].

3. Measurement of the four-lepton production cross section at $\sqrt{s} = 8$ TeV

The inclusive production of four isolated charged leptons (either electrons or muons) is presented in this section in pp interactions at $\sqrt{s} = 8$ TeV with the data corresponding to an integrated luminosity of 20.3 fb^{-1} [8]. The 4l signal events may originate from the decay of resonant Z and Higgs bosons and the non-resonant ZZ continuum produced from $q\bar{q}$, gg and qg initial states.

The integrated and differential cross sections are measured in the mass range $80 < m_{4l} < 1000$ GeV, the latter as functions of invariant mass (m_{4l}) and of transverse momentum (p_T^{4l}). The measurement of the integrated cross section is first performed in the experimental fiducial phase space and then extended to a common phase space which is identical for the three channels, 4e, 4μ and 2e2μ. The pairing of the leptons in the 4e and 4μ cases is performed using the same minimization method as the one used at 13 TeV.

The dominant reducible backgrounds for this analysis originate from Z+jets and $t\bar{t}$ processes, both of which are estimated from data-driven methods. The contributions from ZW, Zγ, tZ as well

4ℓ	Measured σ^{fid} [fb]	SM σ^{fid} [fb]	Measured σ^{ext} [fb]	SM σ^{ext} [fb]
$4e$	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.4	$17.8^{+2.1}_{-2.0}$ (stat) $^{+1.5}_{-1.1}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
4μ	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.5	$17.3^{+1.5}_{-1.4}$ (stat) $^{+0.9}_{-0.7}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
$2e2\mu$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 0.9	$37.7^{+2.7}_{-2.6}$ (stat) $^{+2.5}_{-2.0}$ (syst) $^{+1.1}_{-1.1}$ (lumi)	32.1 ± 2.0
Total			73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

Table 2: The measured cross sections distributions in the fiducial phase space and extended phase space, for the three channels compared with the theoretical Standard Model predictions. The combined measurement for all channels is also included. All results agree with the theoretical predictions. Table taken from [8].

as from the irreducible backgrounds from $t\bar{t}Z$, VVV and ZH are estimated with the use of MC samples.

Table 2 summarizes the measured cross sections in the fiducial and extended phase spaces for the three four-lepton channels along with the theoretical SM predicted cross sections.

Figure 2 presents the measurements of the differential cross sections performed in the fiducial phase space. The events from the three channels are combined into a common sample for the unfolding procedure, which is done as a function of m_{4l} and p_T^{4l}. The data points shown in the figures are the measurements with combined statistical and systematic uncertainties. All measurements agree with the theoretical predictions.

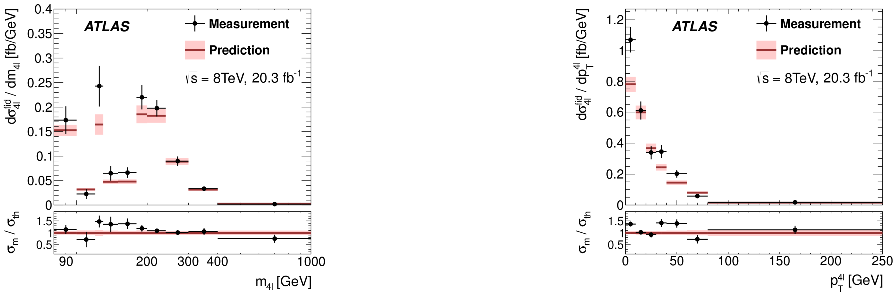

Figure 2: The measured differential cross sections distributions, represented by the black points, of m_{4l} (left) and p_T^{4l} (right) unfolded into the fiducial phase space, and compared to the theoretical predictions, represented by the red histogram. Figures taken from [8].

3.1 $gg \to 4l$ signal contribution

The extraction of the signal strength (i.e. the measured cross section divided by the LO prediction) of the non-resonant $gg \to 4l$ production is performed in the mass region above 180 GeV where this production mode is dominated by the continuum $gg \to ZZ$ process. In order to extract the gg signal strength, the m_{4l} spectrum is used.

The contribution of the $q\bar{q} \to ZZ$ production is constrained to the best contemporary theory knowledge and the signal strength is extracted from a likelihood fit using the reconstructed m_{4l} distributions. The m_{4l} distribution of the data, the fit, the expectation from non-gg signal processes and the background are shown in Figure 3. The fit result is $\mu_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)$ which corresponds to a gg-initiated cross section of 3.1 fb.

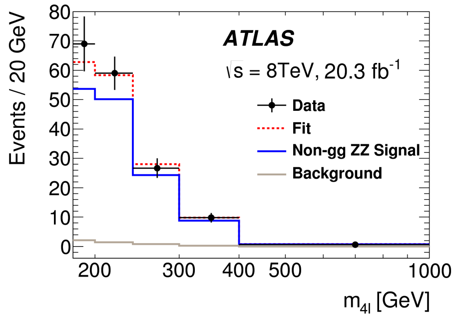

Figure 3: Comparison of the m_{4l} spectra between the data, signified by the black points, and the prediction, signified by the red histogram, after the likelihood fit of μ_{gg}. The non-gg signal from the theoretical prediction, the blue histogram, and the background, the brown histogram, are also shown. The gg contribution is the difference between the data and the sum of the non-gg signal and the background. Figure taken from [4].

4. Measurement of the $Z\gamma$ production cross section at $\sqrt{s} = 8$ TeV

This section presents the measurements on the production of a Z boson associated with an isolated photon [4]. The measurements use 20.3 fb^{-1} of data at a center-of-mass energy of $\sqrt{s} = 8$ TeV. The analysis uses two decay channels: the $Z/\gamma^* \to l^+l^-$, where the leptons can be either electrons or muons, and the invariant mass of the pair must be above 40 GeV, and $Z \to \nu\bar{\nu}$ channel. The Z/γ^* decays to charged leptons are selected using triggers on high p_T electrons or muons. The production channel studied is $pp \to l^+l + X$ where the photons are required to have $E_T > 15$ GeV. The events where the Z boson decays to neutrinos are selected using high-E_T photon triggers. The production channel studied is $pp \to \nu\bar{\nu}\gamma + X$ where the photons must have $E_T > 22$ GeV. In both production channels, the photons are required to be isolated and to satisfy tight identification criteria.

The dominant backgrounds arise from events with jets or electrons misidentified as photons, as well as W $(\to l\nu)\gamma$ events where the lepton from the W decay is not detected. These backgrounds are evaluated using data-driven techniques. The cross sections for the above processes are measured in a fiducial region, for both the inclusive case in which no requirements are placed on the recoil system X, and the exclusive case in which the selected events do not have jets with $p_T > 30$ GeV within $|\eta| < 4.5$. Figure 4 presents the differential cross sections as a function of the photon E_T for the inclusive and exclusive measurements of the $\nu\nu\gamma$ channel.

The data are compared to SM predictions using a parton shower Monter Carlo (SHERPA), or parton-level perturbative calculations carried out at NLO (MCFM), or NNLO calculations by MMHT2014, corrected by parton-to-particle scale factors [4]. There is good agreement between the measurements and the SM predictions.

Since no significant deviations from SM predictions have been observed, the data are used to set limits on anomalous triple gauge couplings (aTGCs) on neutral gauge couplings in the Zγ vertex. These could result from Z/γ^* s-channel production coupled to a final-state Z boson and a photon. The limits on the aTGCs are determined using a modified SM Lagrangian with operators proportional to parameters conventionally denoted as h_3^V and h_4^V where V = Z or γ. The results are

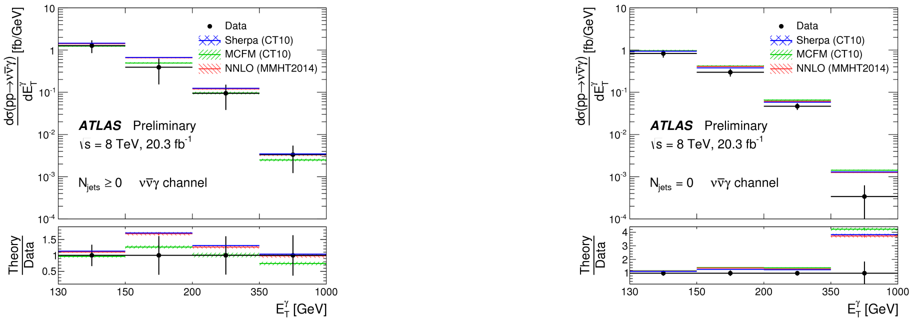

Figure 4: The measured and expected differential cross sections as a function of E_T^{γ} in the inclusive ($N_{jets} \geq 0$) and exclusive ($N_{jets} = 0$) extended fiducial regions. Figures taken from [4].

shown in Figure 5 along with the previous results from the ATLAS and CMS experiments.

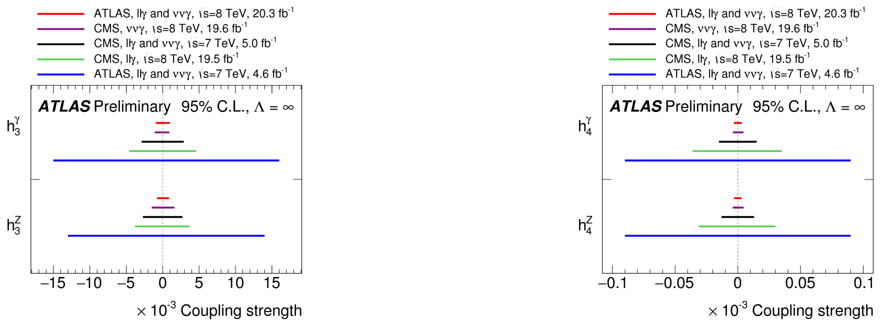

Figure 5: The 95% C.L. nonunitarized intervals, with no form factor used ($\Lambda = \infty$), for anomalous couplings from current and previous ATLAS results and CMS results for the neutral aoTGCs h_3^{γ}, h_3^{Z} (left) and h_4^{γ}, h_4^{Z} (right), as obtained from $Z\gamma$ events. Taken from [4].

5. Conclusions

Recent ATLAS measurements on the $ZZ^{(\star)}$ and $Z\gamma$ production were presented here. ATLAS has measured the ZZ production cross section at 13 TeV in pp collisions at LHC, using 3.2 fb^{-1} of data on the fully leptonic decay channel $ZZ \to l^+l^-l^+l^-$ [2]. The fiducial and total cross section of ZZ pair production with Z boson mass $66 - 116$ GeV have been measured and agree well with predictions.

The measurement of four lepton production at $\sqrt{s} = 8$ TeV using data corresponding to an integrated luminosity of 20.3 fb^{-1} is performed in a fiducial and an extended phase space [8]. The measurements of the 4l differential cross sections are performed by unfolding the spectra of m_{4l} and p_T^{4l}. Furthermore, the signal strength of the gluon-fusion component with respect to the LO prediction is extracted.

The last analysis presents the production of the Z boson along with an isolated high-energy photon at $\sqrt{s} = 8$ TeV using 20.3 fb^{-1} of data [4]. The fiducial $Z\gamma$ cross section is calculated for the cases of $Z/\gamma^* \to l^+l^-$ and $Z \to \nu\bar{\nu}$ with good agreement between the measurements and the SM predictions. No deviations from Standard Model predictions are observed and, consequently, limits are placed on the parameters used to describe anomalous triple gauge couplings.

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