ZZ PRODUCTION CROSS SECTION AT 8 TEV WITH THE ATLAS DETECTOR

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The latest measurement of the Standard Model ZZ production cross section at 8 TeV using data recorded by the ATLAS experiment at the Large Hadron Collider is presented. Events are selected consistent with two Z bosons decaying to electrons or muons. The cross section is measured in the experimental fiducial volume and then used to extract the total ZZ production cross section.

1 The ZZ production

The production of Z boson pairs in the ATLAS Experiment at the Large Hadron Collider (LHC) is of great interest since it provides an excellent opportunity to test the predictions of the electroweak sector of the Standard Model (SM) at the TeV energy scale. Deviations from SM expectations for the total or differential SM production cross sections could be indicative of the production of new resonances decaying to Z bosons or other non-SM contributions. In the SM, ZZ production proceeds via quark-antiquark t-channel interaction, with a small contribution from gluon fusion, calculated using MCFM [1] to be 5.9% in pp collisions at 8 TeV. The ZZZ and $ZZ\gamma$ neutral triple gauge boson couplings (nTGCs) are zero in the SM, hence there is no contribution from s-channel $q\bar{q}$ annihilation at tree level. At the one-loop level, the contribution is $O(10^{-4})$ [2]. Many models of physics beyond the SM predict values of nTGCs at the level of 10^{-4} to 10^{-3} [3]. Those non-zero nTGCs can increase the ZZ cross section especially for high ZZ invariant mass and high transverse momentum of the Z bosons [4].

2 The ATLAS detector

The ATLAS detector is a general purpose particle detector of LHC. It comprises a fine granularity tracking system, an electromagnetic and a hadronic calorimeter, and a muon spectrometer. ATLAS detector shows high combined performance of its subsystems which allows for good identification of electrons and muons. The detector is described in detail elsewhere [5].

3 Event Selection

Events are required to have exactly four high-p_T, isolated electrons or muons, and are selected with at least one triggered muon or electron having $p_T > 25\,GeV$ and being within the triggerable η volume of the detector ($|\eta| < 2.5$ for electrons and $|\eta| < 2.4$ for muons). The other leptons' p_T requirements are lower, as it is explained in this section, in order to increase the signal event yield. To ensure that they originate from the primary vertex, lepton candidates are required to have the absolute value of the product of the longitudinal impact parameter (distance of closest approach) with respect to the primary vertex times the sine of the polar angle θ to be less than 0.5 mm. The primary vertex is defined as the vertex whose constituent tracks have the largest sum of p_T^2. To reject heavy flavour background, muons must have an impact parameter significance (the transverse impact parameter, d_0, divided by its error) less than 3 while the electrons must have an impact parameter significance less than 6.

Muons are identified by tracks (or track segments) reconstructed in the muon spectrometer matched to tracks reconstructed in the inner detector, and are required to have $p_T > 7\ GeV$ and $|\eta| < 2.5$. In order to reject muons from the decay of heavy quarks, it is required that isolated muons are selected by restricting the scalar sum of the transverse momenta (Σp_T) of other tracks inside a cone of $\Delta R = 0.2$ around the muon to be no more than 15% of the muon p_T. In the region $|\eta| < 0.1$ (where there is a limited geometric coverage in the muon spectrometer) calorimeter-tagged muons are considered in addition. They are reconstructed from calorimeter energy deposits consistent with a muon [6] which is matched to an inner detector track with $p_T > 20\ GeV$ and are required to satisfy the same impact parameter and isolation criteria as for the combined muons. Muons with $2.5 < |\eta| < 2.7$ (in a region outside the nominal coverage of the inner detector) are taken into account as well and are required to have $p_T > 10\ GeV$. Instead of the above mentioned Σp_T isolation criteria, the ΣE_T of calorimeter energy deposits inside a cone of size $\Delta R = 0.2$ around these muons is required to be no more than 15% of their p_T. The same impact parameter requirements as for the muons with $|\eta| < 2.5$ are imposed for the forward muons that are measured in the inner detector; no such requirement is imposed on those measured in the muon spectrometer only. The number of calorimeter-tagged muons and muons with $2.5 < |\eta| < 2.7$ per event is limited to a maximum of one of either type and it is also required that they be paired with muons which are neither calorimeter-tagged nor in the forward region, $2.5 < |\eta| < 2.7$. The inclusion of these two types of muons increases the expected event yield by 10%.

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter matched to a track in the inner detector. Electron candidates are required to have $p_T > 7\ GeV$ and $|\eta| < 2.47$. They must be isolated, using the same criteria as for muons within $|\eta| = 2.5$, calculating Σp_T around the electron track. Electron candidates within $\Delta R = 0.1$ of any selected muon are rejected, and if two electron candidates overlap within $\Delta R = 0.1$ the electron with the lower p_T is rejected. The electron identification algorithm was chosen to maximize efficiency at the cost of reduced electron-like jet rejection and is relaxed compared to the identification algorithm used in the ATLAS $H \to ZZ^* \to l^+l^-l'^+l'^-$ analysis [7].

Same-flavour, oppositely-charged lepton pairs are combined to form Z candidates. An event must contain two such pairs. In the $e^+e^-e^+e^-$ and $\mu^+\mu^-\mu^+\mu^-$ final states there is an ambiguity in pairing the leptons into Z bosons. It is resolved by choosing the pairing which results in the smaller value of the sum of the two $|m_{l^+l^-} - m_Z|$ values, where $m_{l^+l^-}$ is the invariant mass of a lepton pair and m_Z is the mass of the Z boson [8]. If any same-flavour, oppositely-charged lepton pairing results in an invariant mass below 5 GeV, the event is rejected to reduce backgrounds including J/Ψ mesons.

4 Background Estimation

The main background to the ZZ signal originates from events with a Z (or $W^\pm$) boson decaying to leptons plus additional jets or photons (referred to as $Z/W^\pm + X$). Events with a top-quark pair, a single-top and other diboson processes (W^+W^-, $W^\pm Z$) also contribute. Jets may be misidentified as electrons or contain electrons and muons from in-flight decays of light mesons or heavy-flavoured hadrons which satisfy the electron or muon object selection. Photons may be misidentified as electrons. Leptons from heavy-flavour decays tend to be rejected by the impact parameter significance requirement. Leptons from misidentified jets or decays of light mesons tend to be spatially correlated with jets and many are rejected by the isolation requirement. Photons tend to be rejected due to hit requirements in the inner detector used in the electron identification. Since Monte Carlo (MC) simulations may not adequately describe the jet fragmentation in the tails of the isolation distributions, the background is estimated directly from the data.

To estimate the background contribution from four-lepton events in which at least one lepton candidate originates from a jet or a photon rather than from the decay of a Z boson, a control sample of events containing three leptons passing all selection criteria plus one $lepton - like\ jet$ and two leptons passing all selection criteria plus two $lepton - like\ jets$ are identified and denoted $lllj$ and $lljj$ respectively. For muons, the lepton-like jets are muon candidates that either fail the track isolation requirement but pass the d_0 significance requirement or fail the d_0 significance requirement but pass the track isolation requirement. For muons with $|\eta| > 2.5$, calorimetric isolation is used instead of track isolation. For electrons, the lepton-like jets are energy deposits in the electromagnetic calorimeter matched to inner detector tracks that either fail the electron identification requirement but pass the track isolation requirement, or fail the track isolation requirement but pass the electron identification requirement. The events are otherwise required to pass the full event selection, treating the lepton-like jet as if it were an identified lepton. Since the selected leptons are spatially separated in ΔR because of the isolation requirements, we require that the lepton-like jets do not overlap with another lepton-like jet or selected lepton within a cone of $\Delta R = 0.2$. This ensures that the control sample has similar kinematic characteristics to the signal sample. This event sample is dominated by $Z + X$ events for the $e^+e^-e^+e^-$ channel and $Z+X$ and $t\bar{t}$ events for the $e^+e^-\mu^+\mu^-$ and $\mu^+\mu^-\mu^+\mu^-$ channels.

The background is then estimated by scaling the control sample by a measured fake factor f (η and p_T dependent, treated as uncorrelated in the two variables) which is the ratio of the probability for background leptons to satisfy the lepton criteria to the probability to satisfy the lepton-like jet criteria, where background leptons are leptons from jets or photons as described above. The background in which two of the selected leptons originate from a jet or photon is treated similarly, using the $lljj$ sample. A correction is necessary to account for the number of ZZ signal events which decay to four leptons where three leptons pass the selected lepton requirements and one passes the lepton-like jet requirements (N_{ZZ}^{lllj}), or two leptons pass the selected lepton requirements and two pass the lepton-like jet requirements (N_{ZZ}^{lljj}). This is estimated using signal Monte Carlo expectation. The background from events with misidentified (fake) leptons is calculated as:

$$N_{4l}^{fake} = N(lllj) \times f - N(lljj) \times f^2 - N_{ZZ}^{Correction} \tag{1}$$

where $N_{ZZ}^{Correction} = N_{ZZ}^{lllj} \times f - N_{ZZ}^{lljj} \times f^2$. The factor f is measured in a sample of data selected by requiring a reconstructed opposite-sign same-flavour lepton pair which has an invariant mass within 20 GeV of the Z mass and classifying any additional identified leptons in the event as selected leptons or lepton-like jets. It is assumed that all of these additional leptons are fakes, either from light jets misidentified as real leptons, bremsstrahlung photons converting to electrons, or from real leptons from decays in heavy flavour jets. Contributions to f from $W^{\pm}Z$ and ZZ processes, which contain additional real leptons, are subtracted from the data using simulation, normalized using the SM cross sections. The systematic uncertainty is determined by comparing the nominal data-driven background estimation using the parameterized fake factor (in η and p_T) and the estimation using the average fake factor (total l divided by total j) for each type of lepton.

Sources of irreducible background such as $t\bar{t}Z$, ZZZ, ZWW must be also taken into consideration when calculating the background estimation. The contribution from these sources is estimated from Monte Carlo and added to the data-driven estimation to give the total background expectation.

5 Results

The numbers of expected and observed events after applying all selection criteria are shown in Table 1, along with the reconstruction acceptance factors used to correct back to the number of events in the fiducial phase-space, taking into account the contribution from events where at least one of the Z bosons decays to τ leptons. We observe 305 candidates passing the ZZ selection in data, with a background expectation of $20.4 \pm 2.9(stat.) \pm 5.0(syst.)$.

Table 1: Summary of observed events, expected signal and background contributions, and reconstruction acceptance factor in all four-lepton channels, after applying the ZZ selection. The signal expectation is derived from Monte Carlo and is shown with the combined statistical and systematic uncertainty. The luminosity uncertainty on the signal expectation is 2.8%.

Final state	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$l^+l^-l'^+l'^-$
Observed	62	85	158	305
Signal (MC)	59.5 ± 4.0	90.2 ± 2.7	142.7 ± 5.6	292.5 ± 10.6
Background	10.0 ± 1.8 ± 1.4	1.1 ± 1.4 ± 0.5	9.3 ± 2.1 ± 3.1	20.4 ± 2.9 ± 5.0
C_{ZZ}	0.55 ± 0.04	0.83 ± 0.03	0.66 ± 0.03	0.68 ± 0.02

The ZZ cross sections are determined using a likelihood fit with the systematic uncertainties included as nuisance parameters. The final result for the fiducial cross section corresponding to the phase-space is:

$$\sigma^{fid}_{ZZ\to l^+l^-l'^+l'^-} = 20.7^{1.3}_{-1.2}(stat.) \pm 0.8(syst.) \pm 0.6(lumi.)\ fb. \tag{2}$$

where $l^+l^-l'^+l'^-$ refers to the sum of the $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$ final states. This result is consistent with the SM prediction $21.1^{+0.9}_{-0.7}\ fb$ calculated at NLO using MCFM, where the error reflects the uncertainty on the PDFs and on the scales.

The total cross section is determined by extrapolating the ZZ fiducial cross section to the full phase-space, correcting for the $Z \to l^+l^-$ branching ratio and the acceptance of the fiducial cuts. The measured value of the total ZZ cross section is:

$$\sigma^{tot}_{ZZ} = 7.1^{+0.5}_{-0.4}(stat.) \pm 0.3(syst.) \pm 0.2(lumi.)\ pb. \tag{3}$$

This result is consistent with the SM prediction of $7.2^{+0.3}_{-0.2}\ pb$ calculated at NLO using MCFM and the CT10 PDF set. Figure 1 shows measurements of the total ZZ production cross section as a function of centre-of-mass energy, showing results from the ATLAS [9] and CMS [10,11] experiments at the LHC, and from the CDF [12] and D0 [13] experiments at the Tevatron, as well as the theoretical predictions.

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References

1. J. Campbell and K. Ellis and C. Williams, *JHEP* **1107**, 018 (2011).
2. G. J. Gounaris and J. Layssac, and F. M. Renard, *Phys. Rev.* D **62**, 073012 (2000).
3. J. Ellison and J. Wudka, *Annu. Rev. Part. Sci.* **48**, 33 (1998).
4. U. Baur and D.L. Rainwater, *Phys. Rev.* D **62**, 113011 (2000).

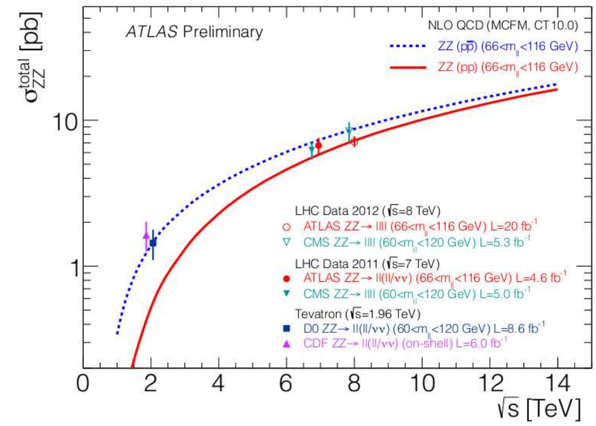

Figure 1: Measurements and theoretical predictions of the total ZZ production cross section as a function of centre-of-mass energy $\sqrt{s}$. Experimental measurements from CDF and D0 in $p\bar{p}$ collisions at the Tevatron at $\sqrt{s} = 1.96\,TeV$, and experimental measurements from ATLAS and CMS in pp collisions at the LHC at $\sqrt{s} = 7\,TeV$ and at $\sqrt{s} = 8\,TeV$ are shown. The blue dashed line shows the theoretical prediction for the ZZ production cross section in $p\bar{p}$ collisions. The solid red line shows the theoretical prediction for the ZZ production cross section in pp collisions[9].

5. ATLAS Collaboration, *JINST* **3**, S08003 (2008).
6. ATLAS Collaboration, ATLAS-CONF-2012-125, https://cds.cern.ch/record/1474642.
7. ATLAS Collaboration, *Phys. Lett.* B **716**, 1-29 (2012).
8. J. Beringer et al. (Particle Data Group), *Phys. Rev.* D **86**, 010001 (2012).
9. ATLAS Collaboration, ATLAS-CONF-2013-020, https://cds.cern.ch/record/1525555.
10. CMS Collaboration, *JHEP* **1301**, 063 (2013).
11. CMS Collaboration, arXiv:1301.4698 [hep-ex].
12. CDF Collaboration, *Phys. Rev. Lett.* **108**, 101801 (2012).
13. D0 Collaboration, *Phys. Rev.* D **85**, 112005 (2012).