Measurement of the $Z \rightarrow \ell\ell$ production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration\textsuperscript{a}

\textsuperscript{a}CERN

Abstract

This note describes the first measurement of the $Z \rightarrow \ell\ell$ production cross section, where $\ell = e, \mu$, by the ATLAS experiment. These results are based on 125 $Z \rightarrow \ell\ell$ candidates, produced in $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC and correspond to a total integrated luminosity of approximately 225 nb$^{-1}$. The total inclusive $Z$-boson production cross section times the charged leptonic branching ratio within the invariant mass window $66 < m_{\ell\ell} < 116$ GeV was measured to be $[0.72 \pm 0.11(\text{stat}) \pm 0.10(\text{syst}) \pm 0.08(\text{lumi})]$ nb for the $Z \rightarrow ee$ channel and $[0.89 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \pm 0.10(\text{lumi})]$ nb for the $Z \rightarrow \mu\mu$ channel, resulting in a combined value of $[0.83 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \pm 0.09(\text{lumi})]$ nb. This constitutes the first $Z$ cross-section measurement by ATLAS in proton-proton collisions at $\sqrt{s} = 7$ TeV and the results obtained are in agreement with theoretical calculations based on NNLO QCD.
1 Introduction

The $W$ and $Z$ bosons are expected to be produced abundantly at the Large Hadron Collider (LHC) [1], and for the first time in proton-proton collisions. The well-known properties of the $Z$ boson will provide significant constraints in the determination of the performance of the collider experiments at the LHC; its known mass, width and leptonic decays can be exploited to determine the detector energy and momentum scale and resolution, as well as lepton identification and trigger efficiencies.

A first measurement of the $W \to \ell \nu$ cross section from the $\sqrt{s} = 7$ TeV proton-proton collisions of the LHC was presented recently [2] by the ATLAS experiment [3]. This note details a measurement of the $Z \to \ell\ell$ cross section by ATLAS. This result is based on 46 $Z \to ee$ and 79 $Z \to \mu\mu$ candidates resulting from a total integrated luminosity of approximately 225 nb$^{-1}$.

2 The $Z$ process and sources of background

The results presented in this note are compared to expectations based on Monte Carlo simulations. The signal and background samples used in this note were generated at $\sqrt{s} = 7$ TeV with PYTHIA [4] using MRSTLO* [5] parton distribution functions (PDF), then simulated with GEANT4 [6] and fully reconstructed. Details of these samples are summarised in Table 1. For the $t\bar{t}$ samples, both MC@NLO [7, 8] and POWHEG [9] were used.

The $Z$ production cross section times its respective $Z/\gamma^* \to \ell\ell$ decay branching ratio used in this study is calculated to next-to-next-to-leading order (NNLO) in QCD using the FEWZ program [10] with the MSTW2008 set of parton distribution functions [11]. The invariant mass of the charged leptons from the process $Z/\gamma^* \to \ell\ell$ is required to be greater than 60 GeV. This value is:

$$\sigma^{\text{NNLO}}_{Z/\gamma^* \to \ell\ell} = 0.99 \text{ nb}. \quad (1)$$

An overall uncertainty of this $Z$ cross section of 4% has been estimated using the MSTW2008NNLO PDF error eigenvectors at the 90% C.L. limit, the NNLO HERAPDF1.0 $\alpha_s$ variations [12], and normalisation and scale variations. In this note, the term “$Z$ cross section” will generically refer to the $Z/\gamma^*$ cross section.

For the electron channel, the primary backgrounds are expected to be from QCD processes, $Z \to \tau\tau, W \to e\nu$, and $t\bar{t}$ production. These background estimates are partially derived from data and by the Monte Carlo samples described in Table 1. For the muon channel, the primary backgrounds are expected to be $Z \to \tau\tau, W \to \mu\nu, t\bar{t}$, and $b\bar{b}$ production. These background estimates are derived from the Monte Carlo samples described in Table 1.

2.1 Event selection

The data presented in this note were collected over a four-month period, from March to July 2010. The basic beam and data-quality requirements as described in Ref. [2] resulted in total integrated luminosities of 219 nb$^{-1}$ for the $Z \to ee$ channel and 229 nb$^{-1}$ for the $Z \to \mu\mu$ channel. The uncertainty on the luminosity determination is estimated to be 11% [13].

Events are selected with the hardware-based L1 trigger as described in Ref. [2] with the following exceptions. The threshold above which the calorimeter trigger accepts electron and photon candidates increased from five to ten trigger counts, where one count corresponds to approximately 1 GeV. The muon trigger, which had no $p_T$ threshold requirement, was changed to one whose $p_T$ threshold is at 6 GeV, as estimated from the hit pattern of multiple chamber layers. As a result of these trigger decisions, a total of $4.4 \times 10^6$ and $3.8 \times 10^6$ events are triggered in the electron and muon channels, respectively.
<table>
<thead>
<tr>
<th>Physics process</th>
<th>Cross section (nb) [× BR]</th>
<th>Luminosity (nb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$ ($m_{\ell\ell} &gt; 60$ GeV)</td>
<td>0.99</td>
<td>$4.8 \times 10^6$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$ ($m_{\ell\ell} &gt; 60$ GeV)</td>
<td>0.99</td>
<td>$5.1 \times 10^6$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$ ($m_{\ell\ell} &gt; 60$ GeV)</td>
<td>0.99</td>
<td>$2.0 \times 10^6$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>10.46</td>
<td>$6.7 \times 10^8$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>10.46</td>
<td>$6.7 \times 10^5$</td>
</tr>
<tr>
<td>Dijet (electron channel, $\hat{p}_T &gt; 15$ GeV)</td>
<td>1.15$\times 10^6$</td>
<td>100</td>
</tr>
<tr>
<td>$b\bar{b}$ (muon channel, $\hat{p}_T &gt; 15$ GeV)</td>
<td>$7.39 \times 10^4$</td>
<td>$59 \times 10^3$</td>
</tr>
<tr>
<td>$c\bar{c}$ (muon channel, $\hat{p}_T &gt; 15$ GeV)</td>
<td>$2.84 \times 10^4$</td>
<td>$53 \times 10^3$</td>
</tr>
<tr>
<td>$t\bar{t}$ (electron channel, MC@NLO)</td>
<td>0.16</td>
<td>$11 \times 10^6$</td>
</tr>
<tr>
<td>$t\bar{t}$ (muon channel, POWHEG)</td>
<td>0.16</td>
<td>$2.5 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 1: Signal and background Monte Carlo samples used in the electron and muon channel analyses, including the production cross section (multiplied by the relevant branching ratios (BR)) and the integrated luminosity of the samples. The variable $\hat{p}_T$ is the transverse momentum of the partons involved in the hard-scattering process. The $Z$ cross section is given at NNLO, the inclusive QCD jet and heavy quark cross sections are given at leading order (LO), and the $t\bar{t}$ cross section at NLO.

Collision candidates are selected by requiring a primary vertex with at least three tracks, consistent with the beam spot position. To reduce fake collision candidates from cosmic-ray or beam-halo events, the muon analysis requires the primary vertex position along the beam axis to be within 15 cm of the nominal position.

For the electron channel, the quality of the reconstruction of the energy deposited by the electron in the liquid argon calorimeter is assessed. The event is rejected if the candidate electromagnetic cluster is located in any problematic region of this detector [2]. These problems can cause extended dead regions in a given layer of the calorimeter, which may have an important impact on the energy reconstruction of the electron. The loss in acceptance due to this requirement is approximately 13%.

### 3 Selection of $Z$ candidates

In the electron channel, pairs are formed from oppositely-charged electron-positron candidates. These lepton candidates are selected with the identification level “medium” as described in Ref. [2] and are required to have a cluster transverse energy $E_T > 20$ GeV within the pseudorapidity range $|\eta| < 2.47$, excluding the transition region between the barrel and end-cap calorimeters ($1.37 < |\eta| < 1.52$).

In the muon channel, pairs are formed from oppositely-charged muon candidates. These lepton candidates are required to be combined muons (stand-alone muon spectrometer tracks associated to an inner-detector (ID) tracks) with transverse momentum $p_T > 20$ GeV as well as have their $p_T$ as measured by the muon spectrometer greater than 10 GeV, within the range $|\eta| < 2.4$. The difference between the inner-detector and muon-spectrometer $p_T$, corrected for the mean energy loss in upstream material, is required to be less than 15 GeV to increase the robustness against track reconstruction mismatches. All muon candidates must satisfy the muon isolation parameter requirement $\Sigma p_T^O / p_T < 0.2$ in a narrow cone of size 0.4 in pseudorapidity-azimuthal angle space. The minimum-$p_T$ used in the isolation requirement is 1 GeV. The difference between the $z$ position of the muon spectrometer tracks extrapolated to the beam line and the $z$ coordinate of the primary vertex is required to be less than 1 cm.

Table 2 summarises the number of $Z \rightarrow \ell\ell$ candidates remaining in data after all requirements have been imposed. A total of 46 candidates pass all requirements in the electron channel and 79 candidates in the muon channel within the invariant mass window $m_{\ell\ell} = 66 – 116$ GeV. Figure 1 shows the electron...
Table 2: Number of $Z \rightarrow \ell \ell$ candidates in data.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triggered</td>
<td>$4.4 \times 10^6$</td>
<td>$3.8 \times 10^6$</td>
</tr>
<tr>
<td>$\ell^+ \ell^-$ pairs</td>
<td>51</td>
<td>85</td>
</tr>
<tr>
<td>$66 &lt; m_{\ell^+\ell^-} &lt; 116$ GeV</td>
<td>46</td>
<td>79</td>
</tr>
</tbody>
</table>

Figure 1: Electron cluster $E_T$ (a) and muon $p_T$ (b) of the $Z$ candidate leptons after final selection.

The invariant mass distribution of these opposite-charged candidate leptons is presented in Figure 3. In Figure 4, a fit is superposed to these data. The data are modelled using the theoretical lineshape, including photon and $Z$ contributions, convolved with a gaussian resolution function. The fitted peak of the distribution is found to be $[88.7 \pm 0.8 \text{(stat)}]$ GeV in the electron channel, and $[89.3 \pm 0.8 \text{(stat)}]$ GeV in the muon channel (with values of 90.6 GeV and 91.2 GeV, respectively, from the Monte Carlo). The experimental resolution is found to be $[3.6 \pm 0.8 \text{(stat)}]$ GeV and $[4.2 \pm 0.8 \text{(stat)}]$ GeV (with values of 1.7 GeV and 1.8 GeV from the Monte Carlo), respectively. These results are within the electromagnetic calorimeter expected energy scale and resolution based on test-beam measurements and first in-situ measurements of $\pi^0 \rightarrow \gamma\gamma$ [14]. The increase of the $Z$ width in the muon channel is due mostly to inner-detector alignment modes affecting high-$p_T$ tracks and misalignments in the forward region of the muon spectrometer.
Figure 2: $p_T$ of the $Z$ candidates in the electron channel (a) and muon channel (b) after final selection.

4 Background expectations for the $Z \rightarrow \ell\ell$ candidates

A partially data-derived estimate of the QCD background is made for the electron channel using the same procedure as described in Ref [2] and using the same QCD scale factor as observed in that measurement. A QCD background Monte Carlo sample is used to estimate the number of pairs of charged leptons that both pass the “loose” electron requirement (as described in Ref. [2]) within the mass window $66 < m_{ee} < 116$ GeV. A data-derived “loose” to “medium” rejection factor for the leptons is then used to estimate the expected number of lepton pairs which both pass the nominal $Z \rightarrow ee$ requirements. The ratio of “medium” to “loose” electrons with $E_T > 20$ GeV within the $\eta$ acceptance of the detector is measured in data to be $0.15 \pm 0.01$(stat). This result is consistent with the equivalent number derived from the QCD background Monte Carlo. In the $Z$ mass window $66 < m_{ee} < 116$ GeV, the Monte Carlo predicts $14.2 \pm 3.4$(stat) QCD background events in the opposite-charge invariant mass distribution for “loose” lepton pairs. By applying the data-derived rejection factors to each electron in these pairs, a background estimate totalling $0.31 \pm 0.07$(stat) $\pm 0.05$(syst) events in the opposite-charge distribution in the $Z$ mass window is derived. Within the mass window $66 < m_{ee} < 116$ GeV, the remaining sources of backgrounds ($W \rightarrow e\nu$: 0.06 events and $t\bar{t}$: 0.08 events) are expected to be flat as a function of the invariant mass while $Z \rightarrow \tau\tau$ background (0.04 events) is expected to drop off sharply. The total expected background within the invariant mass window $66 < m_{ee} < 116$ GeV is then $0.49 \pm 0.07$(stat) $\pm 0.05$(syst) events.

The total number of expected background events in the muon channel within the mass window $66 < m_{\mu\mu} < 116$ GeV after all requirements as estimated from Monte Carlo samples described in Table 1 is $0.17 \pm 0.01$(stat) $\pm 0.01$(syst) and consists of $t\bar{t}$ (0.08 events), $Z \rightarrow \tau\tau$ (0.06 events), $b\bar{b}$ (0.02 events), and $W \rightarrow \mu\nu$ (0.01 events). All other sources of background are negligible in comparison.

The number of same-charge lepton pairs that otherwise satisfy all other requirements is a good indicator of the level of background in the selection. In the electron channel, only one same-charge lepton pair (at $m_{ee} = 82.8$ GeV) satisfies all $Z$ selection requirements within the invariant mass window while there are none in the muon channel.
Figure 3: Invariant mass $m_{\ell\ell}$ of $Z$ candidates in the electron (a) and muon (b) channels.

5 Cross-section measurements for $Z$-boson decays to electrons and muons

5.1 Introduction

The $Z$-boson cross-section measurement is given by:

$$\sigma_{\text{tot}} = \sigma_{Z/\gamma^*} \times \text{BR}(Z/\gamma^* \rightarrow \ell\ell) = \frac{N_{\text{sig}}}{A_Z C_Z L_{\text{int}}},$$

where $\sigma_{\text{tot}}$ is measured within the invariant mass window $m_{\ell\ell} = 66 - 116$ GeV and

- $N_{\text{sig}}$ denotes the number of background-subtracted signal events in the channel of interest, as summarised in Table 4;

- $A_Z$ denotes the so-called geometrical acceptance for the $Z$-boson decays under consideration, defined as the fraction of decays satisfying the geometrical and kinematical (fiducial) constraints at the generator level. These include the $\eta$ requirements as given in Section 3, as well as requirements on $p_T^{\ell} > 20$ GeV for the electron and muon channels. These acceptance values are calculated within the invariant mass window $m_{\ell\ell} = 66 - 116$ GeV and can only be determined from $Z \rightarrow \ell\ell$ Monte Carlo simulation at generator level;

- $C_Z$ denotes the ratio between number of signal events which pass the final selection requirements after reconstruction and the total number of generated events within the geometrical acceptance. In this note, $C_Z$ is estimated using Monte Carlo signal simulation, but this correction factor includes the efficiency for triggering on lepton candidates as well as reconstructing/identifying $Z$-boson decays falling within the geometrical acceptance. In this note, the correction factors $C_Z$ are taken from simulation for the electron channel, but some data-derived corrections are used for the muon channel, as described in Section 5.3. The effect of final state radiation (QED) and event migration from outside the mass window, evaluated with the full simulation of the detector, is also absorbed into this factor;

- and $L_{\text{int}}$ denotes the integrated luminosity for the channel of interest.
Figure 4: Invariant mass $m_{\ell\ell}$ of $Z$ candidates in the electron (a) and muon (b) channels. The data are modelled using the theoretical lineshape, including photon and $Z$ contributions, convolved with a gaussian resolution function.

The geometrical acceptance $A_Z$, as well as the denominator of $C_Z$, are computed at the Born level, i.e. from lepton kinematics before QED corrections. The factor $C_Z$ thus includes the corrections for the final state radiation.

Equation 2 defines the measured total inclusive cross sections for each channel, $\sigma_{\text{tot}}$, measured within the invariant mass window $m_{\ell\ell} = 66 - 116$ GeV and. Equation 2 with the geometrical acceptance $A_Z$ set to unity defines the measured fiducial inclusive cross sections $\sigma_{\text{fid}}$ for each channel. These fiducial cross sections do not rely strongly on any theoretical prediction for the geometrical acceptance and therefore do not contain significant theoretical uncertainties related to it. Cross-section results in this note will be presented for both the electron and muon channels.

5.2 Electron efficiencies and systematic uncertainty on $C_Z$

The correction factor $C_Z$ includes as a primary component the efficiency for reconstructing and identifying $Z$-boson decays falling within the geometrical acceptance. An important efficiency component for the electron channel is the “medium” electron reconstruction/identification efficiency measured with respect to all reconstructed electron candidates. Its average value is 0.863. A total systematic uncertainty of $\pm 11\%$ is assigned to the “medium” electron identification efficiency and comes from material interaction effects upstream of the calorimeter, the impact of event pile-up in the detector, as well as observed discrepancies in the electron identification variables, as mentioned below. This “medium” electron identification efficiency is calculated with respect to all reconstructed candidate electrons and so additional factors must be taken into account for electrons that are in the acceptance but, due to various effects, fail to be reconstructed as candidate electrons. Important sources of loss are due to problematic regions of the calorimeter as specified in Section 2.1 as well as kinematic and $E_T$ requirements. Other sources of loss are due to the mass window and opposite-charge requirements. The correction factor $C_Z$ in addition accounts for the very small inefficiencies for selecting collisions with a reconstructed primary vertex and also includes contributions from trigger effects. The total systematic uncertainty on $C_Z$ is then the sum in quadrature of the following contributions:
• **Trigger efficiency:** The trigger efficiency has been measured in data to be \((99.8 \pm 0.2)\%\);

• **Discrepancies in electron identification variables:** Some discrepancies in electron identification variables have been observed for both electron and photon candidates. A systematic uncertainty was obtained by shifting the observed shapes for the Monte Carlo signal electrons from \(Z\)-boson decay to match those observed for electron candidates in the same kinematic range in data. A systematic uncertainty of \(\pm 10\%\) is assigned to \(C_Z\);

• **Pile-up:** The impact of pile-up on the “medium” electron identification efficiency is evaluated with dedicated pile-up Monte-Carlo samples. A total systematic uncertainty of \(\pm 2\%\) is assigned to \(C_Z\);

• **Material effects:** The impact of possible extra material in the inner detector and in front of the active EM calorimeter has been evaluated with a dedicated simulation as described in Ref. [2]. There are two components that contribute to the overall systematic uncertainty due to this effect: impact on the reconstruction of candidate electrons and on the “medium” electron identification efficiency. A total systematic uncertainty of \(\pm 8\%\) is assigned to \(C_Z\);

• **Problematic regions in the calorimeter:** An additional uncertainty is attributed to electrons that fail to be reconstructed due to problematic regions in the liquid argon calorimeter. A total systematic uncertainty of \(\pm 4\%\) is assigned to \(C_Z\);

• **Energy scale and resolution:** The impact of the electron scale and resolution is dominated by the estimated uncertainty on the EM calorimeter energy scale of \(\pm 3\%\) based on test-beam measurements and first in-situ measurements of \(\pi^0 \to \gamma\gamma\) [14]. Varying the energy scale by this factor provides an uncertainty of \(\pm 2\%\) on \(C_Z\).

In summary, the final correction \(C_Z\) is 0.645 with a total systematic uncertainty of \(\pm 14\%\).

### 5.3 Muon efficiencies, scale factors, and uncertainty on \(C_Z\)

Several important components such as muon reconstruction and trigger efficiencies feed into the evaluation of \(C_Z\) and its systematic uncertainty. These efficiencies have been determined in Monte Carlo and corrected by data-driven scale factors to take into account differences between data and simulation. The muon reconstruction efficiency as determined from the Monte Carlo and corrected by the scale factor is \(0.98 \pm 0.01\) (stat) \(\pm 0.03\) (syst). This scale factor of \(1.00 \pm 0.01\) (stat) \(\pm 0.03\) (syst) was obtained from efficiency studies of isolated combined muon tracks relative to inner detector tracks matched to muon hits in the muon spectrometer which reduce the contribution of fake muons. The inner-detector track efficiency and the muon hit efficiency are considered well modelled in the Monte Carlo, and a systematic is assigned to the level of agreement of this assumption.

The trigger efficiency of \(0.84\pm 0.01\) (stat)\(\pm 0.02\) (syst) was obtained by correcting the value obtained in Monte Carlo with the correction factors \(0.98 \pm 0.01\) (stat) \(\pm 0.02\) (syst) measured from data. These results have been derived by comparing the relative trigger efficiency for reconstructed muons above 15 GeV in data and simulations for both barrel and end-cap trigger systems.

The systematic uncertainty on \(C_Z\) comes in part from the uncertainties on the reconstruction and trigger efficiencies mentioned above. Other effects are due to inefficiencies for selecting collisions with a reconstructed primary vertex, as well as the muon scale and resolutions. The total systematic uncertainty on \(C_Z\) is then the sum in quadrature of the following contributions:

• **Muon reconstruction:** This systematic uncertainty of \(\pm 7\%\) is dominated by the dependence of the efficiency on the transverse momenta and the uncertainty on the remaining \(\pi/K\) contamination in the data sample where the efficiency is measured;
Table 3: Summary of geometrical acceptance values $A_Z$ for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ using various Monte-Carlo simulations.

<table>
<thead>
<tr>
<th>MC</th>
<th>$A_Z$</th>
<th>$A_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA MRSTLO*</td>
<td>0.446</td>
<td>0.486</td>
</tr>
<tr>
<td>MC@NLO HERAPDF1.0</td>
<td>0.440</td>
<td>0.479</td>
</tr>
<tr>
<td>MC@NLO CTEQ6.6</td>
<td>0.445</td>
<td>0.485</td>
</tr>
</tbody>
</table>

- **Trigger efficiency**: This uncertainty of $\pm2\%$ is derived by changing the tolerance on the matching between tracks and trigger signals and comparing measurements obtained in different trigger data streams. This number is a weighted average of the barrel and end-cap trigger efficiency uncertainties, taking into account that there are two muons that can pass the trigger requirements;

- **Energy scale and resolution**: This uncertainty estimation is obtained by applying a smearing of Monte Carlo muon momentum resolution and scale using parameters in agreement with the data (energy scale uncertainty of 2% and a resolution uncertainty of 5% in the barrel and 8.5% in the end-cap [15]) A systematic uncertainty of $\pm1\%$ is assigned to $C_Z$.

The final $C_Z$ is 0.797 with a total systematic uncertainty of $\pm7\%$.

5.4 Geometrical acceptance and uncertainty

The calculation of the total cross section takes into account the phase-space requirements applied in the fiducial cross-section measurement and is entirely based on Monte-Carlo simulations. This geometrical acceptance factor, $A_Z$, is defined as

$$A_Z = \left( \frac{N_{\text{acc}}}{N_{\text{all}}^{\text{gen}}} \right),$$

where $N_{\text{acc}}$ is the number of generated events that pass the fiducial requirements (accepted events as defined in Section 3) and $N_{\text{all}}^{\text{gen}}$ is the total number of generated events (both values are calculated within the mass window $66 < m_{\ell\ell} < 116$ GeV). The effect of event migration from below and above the mass window is taken into account in $C_Z$, which has been evaluated using events generated with $\sqrt{s} > 60$ GeV. The quantity $A_Z$ is determined before the final-state radiation and the losses due to this effect become a component of the $C_Z$, evaluated with the full simulation of the detector response [16].

The acceptance is calculated using the PYTHIA $Z$ samples generated with the modified LO parton distribution function (PDF) MRSTLO* [5] and the corresponding ATLAS MC09 tune [17]. The central values of the acceptances are provided in Table 3. The statistical uncertainty resulting from the Monte Carlo sample is negligible.

The systematic uncertainties on the acceptance are dominated by the limited knowledge of the proton PDFs and the modelling of the $Z$-production at the LHC. These uncertainties are evaluated using dedicated MC@NLO [18] samples generated with two different NLO PDFs: the CTEQ6.6 PDF [19] and HERAPDF1.0 [20]. The acceptance results determined with these alternate PDFs are presented in Table 3.

The systematic uncertainty on the acceptance is derived from the following sources:

- The difference for the MC@NLO acceptances using the two PDFs is 1.3%;
- The uncertainty due to the CTEQ6.6 PDF error eigenvector sets on $A_Z$ is evaluated using a PDF reweighting technique and is estimated to be $\pm1.6\%$;
- The MC@NLO HERAPDF1.0 acceptance values are smaller than PYTHIA values by 1.5%.

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Table 4: Results for the fiducial cross sections $\sigma_{\text{fid}}$ and total cross section $\sigma_{\text{tot}}$ for $Z$ in the electron and muon channels. Shown are the observed numbers of signal events after background subtraction for each channel, the average correction factors $C_Z$, the fiducial cross sections, the geometrical acceptance correction factors, and the total cross sections with their statistical, systematic, and luminosity uncertainties quoted in that order.

These components added in quadrature result in systematic uncertainties on the acceptance values of 2.5%. Due to the limited choice of samples and knowledge about correlations between the contributions, the acceptance-related uncertainty on the $Z$ cross-section measurement is taken to be 3%, motivated by studies from Ref. [2].

5.5 Measured cross sections

All of the elements necessary to calculate the fiducial and total cross sections for $Z$ production and decay in the electron and muon channels are summarised in Table 4. The background-subtracted number of signal events consists of the 46 (79) observed candidates events in the electron (muon) channel as given in Table 2 minus the 0.49 (0.17) background events in the electron (muon) channel as described in Section 4.

The derived fiducial and total cross sections for both the electron and muon channels within the invariant mass window $66 < m_{ee} < 116$ GeV are also presented in this table, along with their statistical, systematic, and luminosity uncertainties. The total cross section value for the combined electron-muon channels, when taking into account the correlated and uncorrelated sources of uncertainty, is $\sigma_{\text{tot}} = [0.83 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \pm 0.09(\text{lumi})]$ nb.

5.6 Comparison to theoretical calculations

A comparison of the measured cross-section value to theoretical predictions including next-to-next-to-leading order QCD corrections is shown in Figure 5 (where the electron and muon channels are shown separately) and Figure 6 (where the electron and muon channels are combined). The calculations were performed with the program FEWZ [10] using the MSTW2008 NNLO parton density function parameterisation [11]. The renormalisation scale $\mu_R$ and factorisation scale $\mu_F$ were chosen to be $\mu_F = \mu_R = m_Z$. Within the experimental uncertainties, the measured cross section agrees well with the calculation $\sigma_{\text{tot}} = (0.964 \pm 0.039)$ nb within the invariant mass window $66 < m_{ee} < 116$ GeV. It should be noted that the theoretical uncertainties resulting from variations of the renormalisation and factorisation scales as well as uncertainties resulting from parton density function parameterisations are not shown in these figures. As discussed in Section 2, these uncertainties are expected to be of the order of $\pm 4\%$ at 7 TeV. Figures 5 and 6 also display the results of previous measurements of the total $Z$ production.
cross section by the CDF [21] and D0 [22] experiments at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider and by the UA1 [23] and UA2 [24] experiments at $\sqrt{s} = 0.63$ TeV at the CERN SpS proton-antiproton collider. All measurements are in good agreement with the theoretical prediction. The energy dependence of the total $Z$-production cross section is well described.

6 Summary

This note presents a measurement by the ATLAS experiment of the $Z \rightarrow \ell\ell$ production cross section based on 125 candidates produced from $\sqrt{s} = 7$ TeV proton-proton collisions at the LHC. These results correspond to a total integrated luminosity of approximately 225 nb$^{-1}$. The total inclusive $Z$-boson production cross section times the charged leptonic branching ratio in proton-proton collisions at $\sqrt{s} = 7$ TeV was measured to be [0.72 ± 0.11(stat) ± 0.10(syst) ± 0.08(lumi)] nb for the $Z \rightarrow ee$ channel and [0.89 ± 0.10(stat) ± 0.07(syst) ± 0.10(lumi)] nb for the $Z \rightarrow \mu\mu$ channel, resulting in a combined result of [0.83 ± 0.07(stat) ± 0.06(syst) ± 0.09(lumi)] nb all measured within the invariant mass window $66 < m_{ee} < 116$ GeV. This constitutes the first $Z$ cross-section measurement by ATLAS in proton-proton collisions and the result obtained is in agreement with theoretical calculations based on NNLO QCD.
Figure 6: The measured value of $\sigma_{Z/\gamma^*} \times \text{BR}(Z/\gamma^* \rightarrow \ell\ell)$ where the electron and muon channels have been combined, compared to the theoretical predictions based on NNLO QCD calculations. The predictions are shown for both proton-proton and proton-antiproton colliders as a function of $\sqrt{s}$. The calculations are based on the FEWZ program with the MSTW2008 NNLO parton density function parameterisations (see text). In addition, measurements at previous proton-antiproton colliders are shown. The data points at the various energies are staggered to improve readability. The data points are plotted with their total uncertainty.

References


[2] The ATLAS Collaboration, G. Aad et al., Measurement of the $W \rightarrow \ell\nu$ production cross-section and observation of $Z \rightarrow \ell\ell$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, ATLAS conference note: ATLAS-CONF-2010-051.


[22] The D0 Collaboration. D0 conference note: D0NOTE4403-CONF.
