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The ATLAS Collaboration

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Keywords:

1. Introduction

At hadron colliders, the Drell–Yan (DY) process $[1]$, proceeding at tree level via the $s$-channel exchange of a virtual photon or $Z$ boson, can produce $e^+ e^-$ pairs over a wide range of invariant mass, $m_{ee}$. The differential cross-section $\sigma/dm_{ee}$ is described by perturbative QCD (pQCD) calculations at next-to-next-to-leading order (NNLO). Given the simple experimental signature and the low backgrounds, a small experimental uncertainty can be achieved on the measured $m_{ee}$ distribution that allows for a precision test of pQCD. The mass spectrum is also sensitive to the parton distribution functions (PDFs), in particular to the poorly known distribution of antiquarks at large $x$ $[2]$, where $x$ can be interpreted, at leading order, as the fraction of the proton momentum carried by the interacting parton. Additionally, the production of DY $e^+ e^-$ pairs is a source of background for other Standard Model (SM) measurements, and the mass spectrum may be modified by new physics phenomena.

The differential cross-section for DY $e^+ e^-$ pair production in the high-mass range has been reported previously by the CMS $[3]$, CDF $[4]$ and D0 $[5]$ collaborations. With the ATLAS detector, total and differential cross-sections in a mass window of 66 < $m_{ee}$ < 116 GeV have been measured using the 2010 dataset $[6]$. In addition, searches for new physics in the high-mass range of the $m_{ee}$ distribution have been performed $[7-9]$, and no deviations from the SM expectation were observed. This Letter reports an extension of these previous analyses by providing a measurement of the DY cross-section, fully corrected for detector effects, as a function of the $e^+ e^-$ invariant mass up to 1500 GeV. The cross-section is reported in a phase space slightly extended with respect to the fiducial acceptance of the $e^+$ and $e^-$. The results are compared to NNLO pQCD calculations with next-to-leading-order (NLO) electroweak corrections from the FEWZ 3.1 $[10, 11]$ framework and to the predictions from three event generators.

2. The ATLAS detector

The ATLAS detector is described in detail in Ref. $[12]$. The two systems most relevant to this analysis are the inner tracking detector, surrounded by a superconducting solenoid providing a 2 T axial magnetic field, and the calorimeter. Charged-particle tracks and vertices are reconstructed with silicon pixel and microstrip detectors covering the pseudorapidity range $|\eta| < 3.2$, and a straw-tube transition-radiation tracker covering $|\eta| < 2.0$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap detectors consisting of lead absorbers and liquid argon (LAr) as the active material, with fine lateral and longitudinal segmentation within $|\eta| < 2.5$. The hadronic calorimeter is based on steel/scintillator tiles in the central region ($|\eta| < 1.7$) while the hadronic endcap calorimeters ($1.5 < |\eta| < 3.2$) use copper/LAr.

A three-level trigger system is used to select events. The first level is implemented in custom electronics and is followed by two software-based trigger levels. In 2011 the total output rate of events recorded for physics analysis was 200–300 Hz.

$^1$ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis coinciding with the axis of the beam pipe. The $x$-axis points from the interaction point to the centre of the LHC ring, and the $y$-axis points upward. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$, and $\phi$ is the azimuthal angle around the beam pipe with respect to the $x$-axis. The angular distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse momentum and energy are defined as $p_T = p \times \sin \theta$ and $E_T = E \times \sin \theta$, respectively.
3. Simulated samples

Simulated data samples were generated in order to estimate backgrounds and correct the signal for the detector resolution, efficiency and acceptance. The PYTHIA 6.426 and MC@NLO 4.02 Monte Carlo (MC) generators were used to model the DY signal. In addition, SHERPA 1.3.1 was used to produce signal samples with up to three additional partons, and the final result of the analysis is compared to the generator-level predictions from all three programs. MC@NLO was also used to simulate the tt background, while HERWIG 6.520 was used for the diboson (WW, WZ or ZZ) backgrounds. MC@NLO was interfaced to HERWIG to model parton showers and fragmentation processes, and to Jimmy 4.31 for underlying event simulations. All event generators were interfaced to PHOTOS 3.0 to simulate QED final-state radiation (FSR), except for SHERPA which uses the method of Ref. [19].

The PYTHIA and HERWIG samples were generated using the modified leading-order (LO**) PDF set MSTWp08 [20] following the recommendations of Ref. [21], while the MC@NLO samples used the NLO CT10 set. The SHERPA samples used the default CTEQ6L1 PDF set of the generator.

All MC events were generated at $\sqrt{s} = 7$ TeV and include the full ATLAS detector simulation [22] based on GEANT4 [23]. Settings of MC parameters that describe properties of minimum bias events and the underlying event were chosen based on results from previous ATLAS measurements [24]. The effects of having on average nine interactions per bunch crossing (“pile-up”) were accounted for by overlaying simulated minimum bias events. To match the measured instantaneous luminosity profile of the LHC, MC events were reweighted to yield the same distribution of the mean number of interactions per bunch crossing as measured in data.

Several corrections were applied to the simulated samples. The electron energy resolution was corrected to match that observed in data, following Ref. [27]. In addition, the efficiencies for electrons to pass requirements on the trigger, the reconstruction, and the particle identification in the MC simulation were corrected by scale factors, defined as the ratio of the measured efficiency in data to that in the simulation. The PYTHIA signal MC sample was reweighted at generator-level to a version that used an ATLAS tune found to yield a good agreement with the transverse momentum distribution of the Z boson observed in data [25]. This procedure gives an adequate description of the transverse momentum distribution for the high $m_{ee}$ region studied in this analysis.

The PYTHIA and MC@NLO signal predictions were reweighted to a NNLO pQCD calculation with $m_{ee}$-dependent K-factors obtained from a modified version of PHOZPR [29]. Additionally, NLO electroweak corrections, calculated using HORACE 3.1 [30], were applied to the PYTHIA MC sample. The $t\bar{t}$ sample was rescaled to its inclusive near-NLO cross-section prediction [31, 32] and the diboson samples were normalised to NLO cross-sections calculated using MCFM [33].

4. Event selection

The analysis is based on the full 2011 data sample collected at $\sqrt{s} = 7$ TeV. The data were selected online by a trigger that required two electromagnetic (EM) energy deposits each with a transverse energy greater than 20 GeV. Applying trigger and data-quality requirements yields an integrated luminosity of $4.9 \pm 0.1$ fb$^{-1}$. Events from these $pp$ collisions are selected by requiring a collision vertex with at least three associated tracks, each with transverse momentum greater than 400 MeV. Events are then required to have at least two electron candidates as defined below.

Electron candidates are reconstructed from the energy deposits in the calorimeter matched to inner-detector tracks. An energy scale correction obtained from an in situ calibration, using W/Z boson and J/ψ meson decays, following the recipe of Ref. [27], is applied to the data. The electron candidates are required to have a transverse energy $E_T > 25$ GeV and pseudorapidity $|\eta| < 2.47$, excluding the transition regions between the barrel and endcap calorimeters at $1.37 < |\eta| < 1.52$. They must satisfy the “medium” identification criteria based on shower shape and track-quality variables [23] to provide rejection against jets, and have a hit in the innermost pixel layer to suppress background from photon conversions.

If an event contains more than two electron candidates passing the above selection, the two with highest $E_T$ are chosen. To further reduce the background from jet production, the leading (highest $E_T$) electron is required to be isolated by demanding that the sum of the transverse energy in the calorimeter cells in a cone of $\Delta R = 0.2$ around the electron direction is less than 7 GeV. This sum excludes the core of the electron energy deposition and is corrected for the $E_T$-dependent transverse shower leakage from the core, as well as for pile-up contributions.

After all selection requirements, a total of 26 844 candidate events are found in the $m_{ee}$ range considered. The dominant background contributions (6–16% depending on $m_{ee}$) are from dijet and W+jets production, in which one or more jets pass the electron selection criteria. The former includes multi-jet, heavy-flavour quark and $\gamma +$ jet production. The latter includes pair-produced top quarks and single-top-quark production, where at least one electron comes from the misidentification of a jet or a heavy quark. A data-driven method is used to evaluate the sum of these backgrounds. The probability of a jet to be misidentified as an electron (the fake rate) is determined in an $E_T$- and $\eta$-dependent way from background-enriched samples recorded by nine different inclusive jet triggers, with

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2In the following electron can mean either electron or positron.
5. Cross-section measurement

The differential cross-section, $\frac{d\sigma}{dm_{ee}}$, is measured in 13 bins of $m_{ee}$ from 116 GeV to 1500 GeV in a fiducial region in which both electrons have transverse momentum $p_T > 25$ GeV and lie within $|\eta| < 2.5$. The cross-section and fiducial region are determined for two conventions regarding QED FSR corrections. For the Born-level result, the true (meaning without detector simulation) $m_{ee}$ and electron kinematics are defined by the electrons originating from the $Z/\gamma^*$ decay before FSR. At the dressed level, true final-state electrons after FSR are recombined with radiated photons within a cone of $\Delta R = 0.1$.

The cross-section is calculated from

$$\frac{d\sigma}{dm_{ee}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{\text{DY}} L_{\text{int}} \Gamma_{\text{bin}}} 1/\Gamma_{\text{bin}},$$

(1)

where $N_{\text{data}}$ is the number of candidate events observed in a given bin of $m_{ee}$ (of width $\Gamma_{\text{bin}}$), $N_{\text{bkg}}$ is the total background in that bin and $L_{\text{int}}$ is the integrated luminosity. The correction factor, $C_{\text{DY}}$, takes into account the efficiency of the signal selection and bin migration effects. It also includes the small extrapolation (about 10% to 13%) over the small region in $|\eta|$ that is excluded for reconstructed electron candidates (1.37 < $|\eta|$ < 1.52 and 2.47 < $|\eta|$ < 2.5). The correction factor is defined as the number of MC-generated events that pass the signal selection in a bin of reconstructed $m_{ee}$, divided by the total number of generated events within the fiducial region, at the Born or dressed level, in the corresponding bin of true $m_{ee}$. It is obtained from the PYTHIA MC signal sample and corrected for differences in the reconstruction, identification and trigger efficiencies between data and MC simulation. The value of $C_{\text{DY}}$ varies from 0.55 (0.57) in the lowest bin to 0.70 (0.73) in the highest bin at the Born (dressed) level.

The $m_{ee}$ resolution varies from approximately 3% at low $m_{ee}$ to 1% at high $m_{ee}$. The purity, defined as the fraction of simulated events reconstructed in a given $m_{ee}$ bin that have true $m_{ee}$ in the same bin, ranges from 79% (82%) to 98% (98%) at the Born (dressed) level.

6. Systematic uncertainties

The main contributions to the systematic uncertainties are given in Table I and described below.

**Background estimation.** In the estimation of the dominant dijet and $W$+jets background, a systematic uncertainty of 11% is assigned to the $E_T$- and $\eta$-dependent fake rate, corresponding to the spread of this quantity as measured in the nine independent jet samples, in order to cover any possible bias introduced in the triggering of these background events. A further uncertainty on the fake rate of up to 11% arises due to the presence of remaining signal contamination in the background-enriched sample.

The total systematic uncertainty on the fake rate combines with a smaller effect (around 5%) from signal contamination in the sample where the fake rate is applied, to give a total uncertainty on the resulting background estimate of up to 16%. An additional systematic uncertainty can arise if the fake rate differs for different sources.
of fake electrons and the relative contribution of the different sources is not the same in the data sample where the fake rate is measured and the sample of events to which it is applied. It is found that \( b \)-jets have a higher fake rate than jets initiated by gluons or light quarks, but that the fraction of \( b \)-jets is small and similar in both samples. Conservatively taking this additional source of uncertainty into account, the overall uncertainty on the background is enlarged to 20%.

This 20% is added in quadrature to the statistical uncertainty of the sample to which the fake rate is applied; the latter uncertainty dominates in the highest two \( m_{ee} \) bins. The resulting overall uncertainty on the cross-section varies between 1.3% and 7.9%, depending on \( m_{ee} \).

Two alternative methods to estimate the dijet and \( W+\)jets background are considered as cross-checks. The first of these is similar to the baseline method but uses fake rates derived from loosely selected electrons collected by the EM signal trigger. Here the background-enriched sample is derived by employing a tag-and-probe technique selecting, among other requirements to suppress real electron contamination, a jet-like tag and a probe with the same charge. This method, being correlated to the baseline method due to the overlap of electron candidates passing the EM and jet triggers, yields very similar predictions with comparable systematic uncertainties. In the third method, the combined dijet plus \( W+\)jets background is estimated by performing a template fit to the isolation of the leading versus sub-leading electron. The background templates are obtained from data by reversing some of the identification requirements on one or both of the electrons, and the signal templates are made from the PYTHIA DY sample. No additional systematic uncertainty is assigned from the two cross-checks, as their results are in agreement with the baseline method.

The uncertainties on the diboson and \( t \bar{t} \) background expectations include the theoretical uncertainties on their cross-sections, 5% for the dibosons \( \eta \) and 10% for \( t \bar{t} \). At high \( m_{ee} \), the statistical uncertainties on the simulated samples dominate, exceeding 50% in the highest bin for both processes. The resulting uncertainty on the cross-section is small compared to the data-driven dijet and \( W+\)jets contributions, ranging from less than 0.3% at low \( m_{ee} \) to 2.0% in the highest \( m_{ee} \) bin. The uncertainty on the cross-section from the total background expectation is between 1.3% and 8.2%.

**Electron reconstruction and identification.** The reconstruction and identification efficiencies of electrons have been determined previously from data for electrons with \( E_T \) up to 50 GeV, using tag-and-probe methods in vector-boson decays, following the prescription of Ref. [27]. To extend the measurement range of the identification efficiency in \( E_T \), a dedicated tag-and-probe measurement is made using \( Z \to \mu^+\mu^- \) decays. It employs the isolation method, developed in Ref. [27] for \( W \to e\nu \) final states, to estimate the background contamination. Here, \( \eta \)- and \( E_T \)-dependent background template distributions of the isolation are obtained from data by reversing some of the requirements applied in the electron identification criteria. The isolation quantity is defined in a similar way to that used in the selection of the leading electron in the signal sample. The background isolation templates are then normalised to data in the tail of the distributions where no contribution from signal is expected, both before and after applying the identification requirements, in order to estimate the background fraction in the probe sample. The identification efficiencies are found to be consistent with those obtained by the method of Ref. [27] in the common measurement range, and are stable for electrons with \( E_T \) up to 500 GeV.

The differences between the measured reconstruction and identification efficiencies and their values in MC simulation are taken as \( \eta \)- and \( E_T \)-dependent scale factors with which the MC-derived \( C_{PY} \) is corrected. An additional scale factor for the isolation requirement on the leading electron is also applied. Varying the scale factors for the electron reconstruction (identification) within their systematic uncertainties results in a change in the cross-section of up to 1.7% (2.6%).

**Energy scale and resolution.** Both the scale and resolution corrections, estimated from \( Z \to e^+e^- \) events, are varied in the simulation within their uncertainties. The overall effect on the cross-section is between 1.0% and 3.3%.

**Bin-by-bin correction.** The results obtained from the bin-by-bin correction are cross-checked using an iterative Bayesian approach [34] and found to be consistent. In addition, a consistency test is performed by correcting the MC@NLO signal sample using the PYTHIA-derived \( C_{PY} \) factor. The discrepancy between the sample corrected in this way and the true MC@NLO sample is about 1.5%. This is due to the slightly different shapes of the \( m_{ee} \) distribution from the two generators, considered to represent the possible

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty [%] in ( m_{ee} ) bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background estimate (Stat.)</td>
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</tr>
<tr>
<td>Total background estimate (Syst.)</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron energy scale &amp; resolution</td>
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<tr>
<td>Electron identification</td>
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<tr>
<td>Electron reconstruction</td>
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<tr>
<td>Bin-by-bin correction</td>
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<tr>
<td>Trigger efficiency</td>
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<tr>
<td>MC statistics (( C_{PY} ) stat.)</td>
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</tr>
<tr>
<td>MC modelling</td>
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</tr>
<tr>
<td>Theoretical uncertainty</td>
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<tr>
<td>Total systematic uncertainty</td>
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<tr>
<td>Luminosity uncertainty</td>
<td>1.8</td>
</tr>
<tr>
<td>Data statistical uncertainty</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 1: Summary of systematic uncertainties on the cross-section measurement, shown for the lowest and highest bin in \( m_{ee} \). For some sources the lowest or highest uncertainty may lie in an intermediate bin. The data statistical uncertainties are also given for comparison.
shape difference between data and the PYTHIA simulation. This is conservatively added as a systematic uncertainty on the cross-section in all \( m_{ee} \) bins.

**Trigger efficiency.** Scale factors to account for the difference in the EM signal-trigger efficiency between data and simulation are obtained by measuring the efficiency in data and MC events using a tag-and-probe method. The \( Z \to e^+e^- \) events are tagged by selecting events passing a single-electron trigger, thus providing one electron probe free of trigger bias to test against the signal-trigger requirements. The scale factors are very close to unity, and the effect on the cross-section of varying them within their systematic uncertainties is approximately 1%.

**MC statistics and MC modelling.** The finite number of events in the MC samples from which the \( C_{DY} \) factor is derived contribute an uncertainty of up to 2.4% on \( C_{DY} \) and the computed cross-section. Systematic uncertainties are associated with the use of the \( K \)-factors and with the reweighting of the PYTHIA signal MC events in order to better match the transverse momentum distribution of the \( Z \) bosons and the mean number of interactions per bunch crossing in the data. The effect of a further reweighting of the vertex position distribution in the \( z \) direction, not applied by default when calculating \( C_{DY} \), is also taken as an uncertainty. These uncertainties enter into the calculation of \( C_{DY} \) and result in an overall uncertainty on the cross-section of less than 1%. Excellent agreement in the FSR predictions between PHOTOS and SANC has been shown [27] and uncertainties related to the modelling of the detector response to low-energy photons from FSR are negligible.

**Theoretical uncertainties.** Several theoretical uncertainties apply to the extrapolation of the cross-section in \( |\eta| \) from the measured region to the fiducial region and thus contribute to an additional uncertainty on \( C_{DY} \). To evaluate the effect of the choice of PDF, the calculation of \( C_{DY} \) using PYTHIA with its default PDF (MRSTMCal) is compared to that obtained after reweighting to CT10 (NLO) and HERAPDF1.5 [38] (NLO). The largest difference between the reweighted results and the default is taken as the systematic uncertainty, and amounts to 0.2%. A further systematic uncertainty is calculated using the MC@NLO sample reweighted to the 52 CT10 eigenvector error sets, the result being 0.5% at most. Finally, comparisons are made between PYTHIA reweighted to the CT10 PDF and MC@NLO (which uses as default CT10), and cross-checked using FEWZ 2.1 at NLO using the CT10 PDF. The effect is at most 0.3%. These systematic uncertainties, which each have a different dependence on \( m_{ee} \), are added in quadrature and together give a 0.2–0.5% uncertainty on the cross-section.

The contributions from the above sources of systematic uncertainty to the uncertainty on the measured cross-section are summarised in Table 2 for the lowest and highest \( m_{ee} \) range considered. The overall systematic uncertainty, excluding the luminosity uncertainty of 1.8% [39], rises from 4.2% in the lowest \( m_{ee} \) bin to 9.8% in the highest \( m_{ee} \) bin. The data statistical uncertainties increase from 1.1% to 50%.

### 7. Results and comparison to theory

The cross-sections obtained in the fiducial region (electron \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \)) at the Born and dressed levels are given in Table 2. The difference between the two results is at most 4%. The precision of the measurement is limited by the statistical uncertainty on the data for \( m_{ee} > 400 \text{ GeV} \).

Fig. 2 shows the results at the dressed level, where they are compared to the predictions from PYTHIA, MC@NLO and SHERPA. No corrections have been applied to the generator-level predictions; instead, the prediction of each generator has been scaled globally to match the total number of events observed in data. The resulting scale factors are 1.23 for PYTHIA, 1.08 for MC@NLO and 1.39 for SHERPA. As expected, the only prediction at NLO in pQCD, from the MC@NLO generator, yields the scale factor closest to unity. The overall shape of the \( m_{ee} \) distribution from all three generators is consistent with the data.

Fig. 3 shows the differential cross-section at the Born level compared to calculations in the FEWZ 3.1 framework using various recent NNLO PDFs. The FEWZ 3.1 framework allows the (N)NLO QCD corrections to lepton pair production to be combined with the NLO electroweak corrections. It has been verified at NLO in QCD that the choice of electroweak scheme, \( G_\mu \) or \( \alpha(m_Z) \) as introduced in Ref. [40], has an effect of at most 0.4% on the calculated cross-section after applying NLO electroweak corrections. The electroweak-corrected NNLO QCD predic-

<table>
<thead>
<tr>
<th>( m_{ee} [\text{GeV}] )</th>
<th>( \frac{d\sigma_{ee}}{dm_{ee}} ) (Born)</th>
<th>( \frac{d\sigma_{ee}}{dm_{ee}} ) (dressed)</th>
<th>Stat. err. [%]</th>
<th>Syst. err. [%]</th>
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<tbody>
<tr>
<td>116–130</td>
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<td>( 2.15 \times 10^{-1} )</td>
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<td>4.2</td>
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<tr>
<td>130–150</td>
<td>( 1.02 \times 10^{-1} )</td>
<td>( 0.84 \times 10^{-2} )</td>
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<tr>
<td>150–170</td>
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<tr>
<td>190–210</td>
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<td>( 1.82 \times 10^{-2} )</td>
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<td>210–230</td>
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<td>( 1.41 \times 10^{-4} )</td>
<td>11.7</td>
<td>5.7</td>
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<tr>
<td>700–1000</td>
<td>( 2.21 \times 10^{-5} )</td>
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<td>7.5</td>
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<td>( 2.76 \times 10^{-6} )</td>
<td>50</td>
<td>9.8</td>
</tr>
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</table>

Table 2: Measured differential cross-sections \( \frac{d\sigma_{ee}}{dm_{ee}} \) (in pb/GeV) at the Born and dressed levels for DY production of \( e^+e^- \) pairs in the fiducial region (electron \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \)) with statistical (stat.) and systematic (syst.) uncertainties in %. The 1.8% luminosity uncertainty is not included.
is dominated by the combined 68% confidence level (CL) PDF and $\alpha_s$ variation. At low $m_{ee}$, the ABM11 [45] prediction lies above this theoretical uncertainty band, in part due to the ABM11 PDF set taking a value of $\alpha_s$ outside of the 68% CL variation. The renormalisation and factorisation scale uncertainties contribute at most 1% to the theoretical uncertainty band in the highest $m_{ee}$ bin, having been evaluated by varying both scales up or down together by a factor of two, using VRAP [46]. The size of the photon-induced contribution is similar to the sum of the PDF, $\alpha_s$ and scale uncertainties as can be seen in the lower panel of Fig. 3 (left), where the nominal calculation using the MSTW2008 PDF set is compared to the case where this contribution is not taken into account.

In the region where the precision of the measurement is limited by systematic uncertainties, $m_{ee} < 400$ GeV, the data generally lie above the FEWZ calculations. However, assuming that all systematic uncertainties, except those of statistical origin on the background and on $C_{DY}$ (Table 1), are fully correlated bin-to-bin, the comparison between data and the different predictions over the full mass range yields chi-squared values of 13.9 for MSTW2008, 18.9 for CT10, 13.5 for HERAPDF1.5, 14.7 for ABM11 and 14.8 for NNPDF2.3, for the 13 data points, indicating compatibility between the theory and data.

8. Summary

Using 4.9 fb$^{-1}$ of data from $p\bar{p}$ collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, the invariant mass distribution of $e^+e^-$ pairs from DY production has been measured at ATLAS in the range $116 < m_{ee} < 1500$ GeV, for electrons with $p_T > 25$ GeV and $|\eta| < 2.5$. Comparisons have been made to the predictions of the PYTHIA, MC@NLO and SHERPA MC generators, after scaling them globally to match the total number of events observed in data. The MC predictions are consistent with the shape of the measured $m_{ee}$ distribution. The predictions of the FEWZ 3.1 framework using five PDF sets at NNLO have also been studied. The framework combines calculations at NNLO QCD with NLO electroweak corrections, to which LO photon-induced corrections and real $W$ and $Z$ boson emission in single-boson production have been added. The resulting predictions for all PDFs are consistent with the measured differential cross-section, although the data are systematically above the theory. The data have the potential to constrain PDFs, in particular for antiquarks at large $x$, in the context of a PDF fit involving the world data sensitive to the proton structure.

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Figure 3: Measured differential cross-section at the Born level within the fiducial region (electron $p_T > 25$ GeV and $|\eta| < 2.5$) with statistical, systematic, and combined statistical and systematic (total) uncertainties, excluding the 1.8% uncertainty on the luminosity. The measurement is compared to FEWZ 3.1 calculations at NNLO QCD with NLO electroweak corrections using the $G_\mu$ electroweak parameter scheme. The predictions include an additional small correction from single-boson production in which the final-state charged lepton radiates a real $W$ or $Z$ boson. On the left, in the upper ratio plot, the photon-induced (PI) corrections have been added to the predictions obtained from the MSTW2008, HERAPDF1.5, CT10, ABM11 and NNPDF2.3 NNLO PDFs, and for the MSTW2008 prediction the total uncertainty band arising from the PDF, $\alpha_s$, renormalisation and factorisation scale, and photon-induced uncertainties is drawn. The lower ratio plot shows the influence of the photon-induced corrections on the MSTW2008 prediction, the uncertainty band including only the PDF, $\alpha_s$ and scale uncertainties. On the right, the results are shown for a restricted range of $m_{ee}$.

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References

Paris, France

80 Fysiska institutionen, Lunds universitet, Lund, Sweden
81 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
82 Institut für Physik, Universität Mainz, Mainz, Germany
83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
85 Department of Physics, University of Massachusetts, Amherst MA, United States of America
86 Department of Physics, McGill University, Montreal QC, Canada
87 School of Physics, University of Melbourne, Victoria, Australia
88 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
89 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
90 (a)INFN Sezione di Milano; (b)Dipartimento di Fisica, Università di Milano, Milano, Italy
91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
93 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
94 Group of Particle Physics, University of Montreal, Montreal QC, Canada
95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
102 (a)INFN Sezione di Napoli; (b)Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Buckler Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Palacký University, RCPTM, Olomouc, Czech Republic
113 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
114 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
115 Graduate School of Science, Osaka University, Osaka, Japan
116 Department of Physics, University of Oslo, Oslo, Norway
117 Department of Physics, Oxford University, Oxford, United Kingdom
118 (a)INFN Sezione di Pavia; (b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
119 Department of Physics, Pennsylvania State University, Philadelphia PA, United States of America
120 Petersburg Nuclear Physics Institute, Gatchina, Russia
121 (a)INFN Sezione di Pisa; (b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
122 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
123 Laboratorio de Instrumentación y Física Experimental de Partículas - LIP, Lisboa, Portugal; (b)Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
124 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
125 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
126 State Research Center Institute for High Energy Physics, Protvino, Russia
127 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
128 Physics Department, University of Regina, Regina SK, Canada
129 Ritsumeikan University, Kusatsu, Shiga, Japan
133 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
134 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
139 Department of Physics, University of Washington, Seattle WA, United States of America
140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
141 Department of Physics, Shinshu University, Nagano, Japan
142 Fachbereich Physik, Universität Siegen, Siegen, Germany
143 Department of Physics, Simon Fraser University, Burnaby BC, Canada
144 SLAC National Accelerator Laboratory, Stanford CA, United States of America
145 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
146 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
147 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
148 Physics Department, Royal Institute of Technology, Stockholm, Sweden
149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
161 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
162 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
163 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
164 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
165 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
166 Department of Physics, University of Illinois, Urbana IL, United States of America
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNMI), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver BC, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom
172 Waseda University, Tokyo, Japan
173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
174 Department of Physics, University of Wisconsin, Madison WI, United States of America
175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
177 Department of Physics, Yale University, New Haven CT, United States of America