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Published in:
Physics Letters B

DOI:
10.1016/j.physletb.2013.07.049

Link to publication

Citation for published version (APA):

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Measurement of the high-mass Drell–Yan differential cross-section in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV with the ATLAS detector

ATLAS Collaboration

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 charged lepton pairs over a wide range of invariant mass. The differential cross-section as a function of the invariant mass 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 invariant mass distribution allowing 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 dilepton pairs is a source of background for other Standard Model (SM) measurements, and the mass spectrum may be modified by new physics phenomena giving rise to, e.g., narrow resonances or an excess of high-mass pairs inconsistent with the known PDFs.

The differential cross-section for DY dilepton 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 66–116 GeV have been measured using the 2010 dataset [6]. In addition, searches for new physics in the high-mass range 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, in the dielectron channel as a function of the \( e^+e^- \) invariant mass, \( m_{ee} \), up to 1500 GeV. To minimise model-dependent theoretical uncertainties, the cross-section is not extrapolated to the full phase space but is reported in a phase space only 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 \( \text{FEWZ} \) [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 polar angle \( \theta \) as \( \theta = -\sin^{-1}(\sin^{2}\theta/2) \), 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.

\( \ast \) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point of 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.
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/liquid argon.

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.

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 [13] and *MC@NLO* 4.02 [14] Monte Carlo (MC) generators were used to model the DY signal. In addition, *SHERPA* 1.3.1 [15] 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 $t\bar{t}$ background, while *HERWIG* 6.520 [16] 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 [17] for underlying event simulation. All event generators were interfaced to *PHOTOS* 3.0 [18] 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 MRSTMCal [20] following the recommendations of Ref. [21], while the *MC@NLO* samples used the NLO CT10 [22] set. The *SHERPA* samples used the default CTEQ6L1 [23] PDF set of the generator.

All MC events were generated at $\sqrt{s} = 7$ TeV and include the full ATLAS detector simulation [24] based on GEANT4 [25]. Settings of MC parameters that describe properties of minimum bias events and the underlying event were chosen based on results from previous ATLAS measurements [26]. 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 independent corrections were applied to the simulated samples, for the detector response, missing higher order terms in the generation of the signal events and for the modelling of the transverse momentum spectrum of the lepton pair. 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* and *MC@NLO* signal predictions were reweighted to a ratio of NNLO pQCD calculation with $m_{ee}$-dependent $K$-factors obtained from a modified version of *PHODPR* [28]. Additionally, NLO electroweak corrections, calculated using *HORACE* 3.1 [29], were applied to the *PYTHIA* MC sample. The $t\bar{t}$ sample was rescaled to its inclusive near-NNLO cross-section prediction [30,31] and the diboson samples were normalised to NLO cross-sections calculated using *MC@NLO* [32]. 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 [33]. This procedure gives an adequate description of the transverse momentum distribution for the high $m_{ee}$ region studied in this analysis.

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 $4.9 \pm 0.1 \text{fb}^{-1}$. 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. The electron energy is measured in the calorimeter and its direction from the associated track. The calorimeter energy resolution is between 1% and 2% for high-energy electrons [27]. An energy scale correction obtained from an in situ calibration, using $W/Z$ boson and $J/\psi$ 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, track-quality and track–cluster matching variables, which are inclusive of the shower shape criteria applied as part of the “loose” identification [27]. Additionally, the electron candidates must have an associated 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 26844 candidate events are found in the $m_{ee}$ range considered. The dominant backgrounds are events containing one or two misidentified electron candidates, denoted $W + \text{jets}$ and dijet. Other backgrounds arise from events containing two real electrons, originating from the dileptonic decays of pair-produced top quarks (denoted $tt\ell$) and from diboson production processes.

Of the dijet and $W + \text{jets}$ background, the dijet component additionally contains multi-jet, heavy-flavour quark and $\gamma + \text{jet}$ production. The $W + \text{jets}$ 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 components. The probability for a jet to be misidentified as an electron (the fake rate) is determined in an $E_T$- and $\eta$-dependent way from nine background-enriched samples recorded by different inclusive jet triggers. These triggers had $E_T$ thresholds in the range 20–240 GeV, each with a different predefined rate achieved via the automatic rejection of a certain fraction of events, such that the nine samples were needed to collect sufficient background events over the full $E_T$ range. In each of these jet-triggered samples, the fake rate is calculated as the fraction of electron candidates passing the “loose” identification requirement that also pass the “medium” requirement. Events containing electron candidates from $W$ or $Z$ boson decays are first removed by dedicated cuts in order to avoid bias from real electron contamination: $W$ candidates are rejected by

\footnote{In the following electron can mean either electron or positron.}
reconstructing the dijet and diboson backgrounds. A weighted average of the fake rates obtained from the
nine jet samples is then calculated. To estimate the total dijet plus
trons. A weighted average of the fake rates obtained from the
sum of the signal and background predictions is shown inFig. 1.
respectively. The overall level of agreement between data and the
ulation and account for up to 5% and 9% of the selected events,
generated events that pass the signal selection in a bin of re-
require low missing transverse energy and low transverse mass;
and Z candidates are rejected if they contain two “medium” elec-
trons. A weighted average of the fake rates obtained from the
nine jet samples is then calculated. To estimate the total dijet plus
W + jets background, a factor derived from the averaged fake rate
is applied to events that pass the signal selection but with one or
both electron candidates passing only the “loose” identification re-
quirement and failing the “medium” requirement.
The t\bar{t} and diboson backgrounds are estimated from MC sim-
ulation and account for up to 5% and 9% of the selected events,
respectively. The overall level of agreement between data and the
sum of the signal and background predictions is shown in Fig. 1.

5. Cross-section measurement

The differential cross-section, 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 deter-
mined for two conventions regarding QED FSR corrections. For
the Born-level result, the true (meaning without detector simu-
lation) 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

\[ \frac{d\sigma}{dm_{ee}} = \frac{N_{data} - N_{bkg}}{C_{DY} L_{int}} \frac{1}{T_{bin}}, \]

where N_{data} is the number of candidate events observed in a given
bin of m_{ee} (of width \Delta T_{bin}), N_{bkg} is the total background in that bin
and L_{int} is the integrated luminosity. The correction factor, C_{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 re-
constructed m_{ee}, divided by the total number of generated events
within the fiducial region, at the Born or dressed level, in the cor-
responding 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 simu-
lation. The value of C_{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 simu-
lated 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 1 and described below.

6.1. Background estimation

In the estimation of the dominant dijet and W + jets back-
ground, a systematic uncertainty of 11% is assigned to the E_{T}\gamma-
and \eta-dependent fake rate, corresponding to the spread of this quan-
tity as measured in the nine independent jet samples, in order to
cover any possible bias introduced in the triggering of these back-
ground 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 sys-
tematic uncertainty can arise if the fake rate differs for different
sources of fake electrons and the relative contribution of the dif-
ferent 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
dominate in the highest two m_{ee} bins. The resulting overall uncer-
tainty on the cross-section from the dijet and W + jets background
varies between 1.3% and 7.9%, depending on m_{ee}.

Two alternative methods to estimate the dijet and W + jets back-
ground 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 sup-
press 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 sam-
ple. 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 expecta-
tions include the theoretical uncertainties on their cross-sections,
5% for the dibosons [30] and 10% for t\bar{t} [31]. 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 \(W + \text{ jets}\) 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%.

### Table 1

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Uncertainty [%] in (m_{ee}) bin</th>
<th>116–130 GeV</th>
<th>1000–1500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background estimate (stat.)</td>
<td>0.1</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Total background estimate (syst.)</td>
<td>1.3</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Electron energy scale &amp; resolution</td>
<td>2.1</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Electron identification</td>
<td>2.3</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>1.6</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Bin-by-bin correction</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>MC statistics ((C_{\text{DY}}) stat.)</td>
<td>0.7</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>MC modelling</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Theoretical uncertainty</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>4.2</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Data statistical uncertainty</td>
<td>1.1</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

### 6.2. 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 \(Z \rightarrow e^+ e^-\) decays. It employs the isolation method, developed in Ref. [27] for \(W \rightarrow e\nu\) 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 \(C_{\text{DY}}\) 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 \(Z \rightarrow e^+ e^-\) events, are varied in the simulation within their uncertainties. The overall effect on the cross-section is between 1.0% and 3.3%.

### 6.4. 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 \(C_{\text{DY}}\) 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 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.

### 6.5. 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 \(Z \rightarrow e^+ e^-\) 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 requirement. 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%.

### 6.6. MC statistics and MC modelling

The finite number of events in the MC samples from which the \(C_{\text{DY}}\) factor is derived contribute an uncertainty of up to 2.4% on \(C_{\text{DY}}\) 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 \(C_{\text{DY}}\), is also taken as an uncertainty. These uncertainties enter into the calculation of \(C_{\text{DY}}\) and result in an overall uncertainty on the cross-section of less than 1%. Excellent agreement in the FSR predictions between PHOTOS and SANC [35,36] has been shown [37] and uncertainties related to the modelling of the detector response to low-energy photons from FSR are negligible.

### 6.7. Theoretical uncertainties

Several theoretical uncertainties apply to the extrapolation of the cross-section in \(|\eta|\) from the measured region to the fiducial

### Table 2

Measured differential cross-sections \(d\sigma_{\text{dressed}}(\text{Born})\) (in pb/GeV) at the Born and dressed levels for \(DY\) production of \(e^+ e^-\) pairs in the fiducial region (electron \(p_T > 25\) GeV and \(|\eta| < 2.5\)) with statistical (stat.) and systematic (syst.) uncertainties in %.

<table>
<thead>
<tr>
<th>(m_{ee}) [GeV]</th>
<th>(d\sigma/dE_{T,\text{dressed}}) [ Born ]</th>
<th>(d\sigma/dE_{T,\text{dressed}}) [ dressed ]</th>
<th>Stat. err. [%]</th>
<th>Syst. err. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>116–130</td>
<td>2.24 \times 10^{-1}</td>
<td>2.15 \times 10^{-1}</td>
<td>1.1</td>
<td>4.2</td>
</tr>
<tr>
<td>130–150</td>
<td>1.02 \times 10^{-1}</td>
<td>9.84 \times 10^{-2}</td>
<td>1.4</td>
<td>4.3</td>
</tr>
<tr>
<td>150–170</td>
<td>5.12 \times 10^{-2}</td>
<td>4.93 \times 10^{-2}</td>
<td>2.0</td>
<td>4.6</td>
</tr>
<tr>
<td>170–190</td>
<td>2.84 \times 10^{-2}</td>
<td>2.76 \times 10^{-2}</td>
<td>2.7</td>
<td>4.7</td>
</tr>
<tr>
<td>190–210</td>
<td>1.87 \times 10^{-2}</td>
<td>1.82 \times 10^{-2}</td>
<td>3.0</td>
<td>5.3</td>
</tr>
<tr>
<td>210–230</td>
<td>1.07 \times 10^{-2}</td>
<td>1.04 \times 10^{-2}</td>
<td>4.4</td>
<td>6.1</td>
</tr>
<tr>
<td>230–250</td>
<td>8.23 \times 10^{-3}</td>
<td>7.98 \times 10^{-3}</td>
<td>5.2</td>
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<tr>
<td>250–300</td>
<td>4.66 \times 10^{-3}</td>
<td>4.52 \times 10^{-3}</td>
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<td>300–400</td>
<td>1.70 \times 10^{-3}</td>
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<td>400–500</td>
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<td>500–700</td>
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<td>700–1000</td>
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<td>1000–1500</td>
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<td>2.76 \times 10^{-6}</td>
<td>50</td>
<td>9.8</td>
</tr>
</tbody>
</table>
region and thus contribute to an additional uncertainty on $C_{FV}$. To evaluate the effect of the choice of PDF, the calculation of $C_{FV}$ using PYTHIA with its default PDF (MRSTMCa1) 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 1 for the lowest and highest bin in the $m_{ee}$ 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 $p_T > 25$ 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 $m_{ee} > 400$ 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 by a global factor as indicated on the ratio plots to match the total number of events observed in data.

The electroweak-corrected NNLO QCD predictions shown are calculated cross-section after applying NLO electroweak corrections. It has been verified at NLO in pQCD, as introduced in Ref. [40], has an effect of at most 0.4% on the prediction of each 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 the 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 predictions shown are calculated using the $G_\mu$ scheme. The electroweak corrections include a positive contribution from the irreducible, non-resonant photon-induced background, i.e., $\gamma\gamma \to e^+e^-$. This contribution is estimated at leading order (LO) using the MRST2004qed [41] PDF, currently the only set available that includes QED corrections to the proton PDF, by taking the average of the predictions obtained under the current and constituent quark mass schemes. The symmetric difference between the average and either scheme is assigned as the corresponding uncertainty on this additive correction, being approximately 50% and representing a 3% uncertainty on the cross-section prediction in the highest $m_{ee}$ bin. The electroweak and photon-induced corrections were verified by SANC [35,36]. An additional small correction arises from single-boson production in which the final-state charged lepton radiates a real $W$ or $Z$ boson [42]. This is estimated using MADGRAPH5 [43], following the prescription outlined in Ref. [42], to be at most 2%, in the highest $m_{ee}$ bin.

It can be seen in Fig. 3 that the deviations between the MSTW2008 [2] and the CT10 [22], HERAPDF1.5 [38] and NNPDF2.3 [44] predictions are covered by the total uncertainty band assigned to the MSTW2008 prediction, which 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 using 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 $C_{FV}$ (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 $pp$ 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
Fig. 3. Measured differential cross-section at the Born level within the fiducial region (electron $p_T > 25$ GeV and $|\eta| < 2.5$) with statistical (error bars), systematic (dark shaded), and combined statistical and systematic (total, light shaded) 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 $G_F$ 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 $m_{ee}$.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; STC, Belarus; CNPq and FAPERJ, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR, DMS, and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3–CNRS, CEA, DAPNIA, and CSC, France; FAPERJ, FAPERGS, FAPESP, and CNPq, Brazil; RSF, RFFR, and FSBI, Russia; MINECO, Spain; DFG, HGF, and MPG, Germany; INFN, Italy; MAIF, Russia; KNCFS and SNSF, Switzerland; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC–IN2P3 (France), KIT/GridKA (Germany), INFN–CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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