

# Measurement of the double-differential high-mass Drell-Yan cross section in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



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**ABSTRACT:** This paper presents a measurement of the double-differential cross section for the Drell-Yan  $Z/\gamma^* \rightarrow \ell^+\ell^-$  and photon-induced  $\gamma\gamma \rightarrow \ell^+\ell^-$  processes where  $\ell$  is an electron or muon. The measurement is performed for invariant masses of the lepton pairs,  $m_{\ell\ell}$ , between 116 GeV and 1500 GeV using a sample of  $20.3 \text{ fb}^{-1}$  of  $pp$  collisions data at centre-of-mass energy of  $\sqrt{s} = 8$  TeV collected by the ATLAS detector at the LHC in 2012. The data are presented double differentially in invariant mass and absolute dilepton rapidity as well as in invariant mass and absolute pseudorapidity separation of the lepton pair. The single-differential cross section as a function of  $m_{\ell\ell}$  is also reported. The electron and muon channel measurements are combined and a total experimental precision of better than 1% is achieved at low  $m_{\ell\ell}$ . A comparison to next-to-next-to-leading order perturbative QCD predictions using several recent parton distribution functions and including next-to-leading order electroweak effects indicates the potential of the data to constrain parton distribution functions. In particular, a large impact of the data on the photon PDF is demonstrated.

**KEYWORDS:** Hadron-Hadron scattering (experiments)

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## 1 Introduction

The Drell-Yan (DY) process [1] of lepton pair production in hadronic interactions,  $pp \rightarrow Z/\gamma^* + X$  with  $Z/\gamma^* \rightarrow \ell^+\ell^-$ , is a powerful tool in understanding the nature of partonic interactions and of hadronic structure in detail. The study of this process has been fundamental in developing theoretical perturbative calculations of quantum chromodynamics (QCD) which are now performed at next-to-next-to-leading-order (NNLO) accuracy [2–5]. Measurements from the Large Hadron Collider (LHC) of neutral- and charged-current Drell-Yan processes mediated by  $Z/\gamma^*$  and  $W$  exchange respectively at centre-of-mass energies of  $\sqrt{s} = 7$  TeV and 8 TeV have been recently published by the ATLAS [6–8], CMS [9–12] and LHCb [13–17] collaborations. These data provide new constraints on the parton distribution functions (PDFs) of the proton, some of which have been used in recent global PDF fits [18–20].

Although on-shell  $Z$  and  $W$  boson measurements provide the greatest experimental precision, they are restricted in the kinematic range of partonic momentum fraction  $x$ , and four-momentum transfer  $Q = m_{\ell\ell}$ , the invariant mass of the dilepton pair. Off-shell measurements provide complementary constraints in a wider range of  $x$  and  $Q$ . In the neutral-current case, the off-shell measurements are dominated by the electromagnetic quark couplings to the virtual photon  $\gamma^*$ , whereas the on-shell measurements are dominated by the weak axial and vector couplings of the quarks to the  $Z$  boson. Therefore, the measurements have different sensitivity to the up-type and down-type quarks. At large  $m_{\ell\ell}$  the measurements offer constraints on the large- $x$  antiquark PDFs which are poorly known. In addition, off-shell measurements may also be sensitive to the largely unconstrained photon PDF [7, 8, 21, 22] through the photon-induced (PI) process  $\gamma\gamma \rightarrow \ell^+\ell^-$ .

Neutral-current DY data at higher masses can also be used to determine the running of the electroweak (EW) gauge couplings above the weak scale, and to set model-independent limits on new states with electroweak quantum numbers [23]. In particular, at the highest invariant masses accessible at the LHC, the observed dilepton spectrum may be sensitive to new physics, which could manifest itself as a resonance or a broad modification to the continuum spectrum. Such searches performed by the ATLAS and CMS experiments [24–26] have so far not found any significant deviations from the Standard Model, and the largest systematic uncertainty on the derived exclusion limits arises from the lack of knowledge of the PDFs at high  $x$ . Since at leading order the parton momentum fractions from the two protons (1 or 2) are given by  $x_{1,2} = (m_{\ell\ell}/\sqrt{s}) e^{\pm y_{\ell\ell}}$ , where  $y_{\ell\ell}$  is the dilepton rapidity, it can be seen that the large  $x$  region is accessible at large  $m_{\ell\ell}$  in the case of central production ( $y_{\ell\ell} = 0$ ), as well as at lower  $m_{\ell\ell}$  and large  $y_{\ell\ell}$ . Therefore, a double-differential measurement of the Drell-Yan cross section in  $m_{\ell\ell}$  and  $y_{\ell\ell}$  provides PDF constraints in a new kinematic region which is expected to be unaffected by the manifestation of potential new physics at the highest invariant mass.

This article reports two inclusive double-differential cross-section measurements for the process  $pp \rightarrow \ell^+\ell^- + X$ . The first measurement is reported as a function of  $m_{\ell\ell}$  and absolute dilepton rapidity  $|y_{\ell\ell}|$ , and the second as a function of  $m_{\ell\ell}$  and absolute dilepton pseudorapidity separation  $|\Delta\eta_{\ell\ell}|$ . These measurements are sensitive to the proton PDFs, the PI process, and higher-order electroweak corrections, which have different kinematic dependencies. In particular, the  $t$ -channel PI process is expected to contribute at large  $|\Delta\eta_{\ell\ell}|$ , small  $|y_{\ell\ell}|$  and large  $m_{\ell\ell}$ . Therefore, measurements as a function of various kinematic distributions are needed to disentangle the different contributions [27]. For completeness the inclusive single-differential measurement  $d\sigma/dm_{\ell\ell}$  is also provided. The measurements are performed using  $pp$  collision data collected at  $\sqrt{s} = 8$  TeV in both electron and muon channels. The data cover the kinematic region of  $116 \leq m_{\ell\ell} \leq 1500$  GeV and access partonic momentum fractions from  $10^{-3}$  up to  $x \sim 1$ . The integrated luminosity of the data sample is  $20.3 \text{ fb}^{-1}$ , a factor five larger than used in the previous ATLAS measurement [7] at  $\sqrt{s} = 7$  TeV performed in the electron channel only. Therefore, the results reported here have a substantially better precision than earlier results.

## 2 ATLAS detector

The ATLAS detector [28] consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). Charged particles in the pseudorapidity<sup>1</sup> range  $|\eta| < 2.5$  are reconstructed with the ID, which consists of layers of silicon pixel and microstrip detectors and a straw-tube transition-radiation tracker having coverage within  $|\eta| < 2.0$ . The ID is immersed in a 2 T magnetic field provided by the solenoid. The latter is surrounded by a hermetic calorimeter that covers  $|\eta| < 4.9$  and provides three-dimensional reconstruction of particle showers. The electromagnetic calorimeter is a liquid-argon sampling calorimeter, which uses lead absorbers for  $|\eta| < 3.2$  and copper absorbers in the very forward region. The hadronic sampling calorimeter uses plastic scintillator tiles as the active material and steel absorbers in the region  $|\eta| < 1.7$ . In the region  $1.5 < |\eta| < 4.9$ , liquid argon is used as active material, with copper or/and tungsten absorbers. Outside the calorimeters, air-core toroids supply the magnetic field for the MS. There, three stations of precision chambers allow the accurate measurement of muon track curvature in the region  $|\eta| < 2.7$ . The majority of these precision chambers are composed of drift tubes, while cathode-strip chambers provide coverage in the inner stations of the forward region for  $2.0 < |\eta| < 2.7$ . Additional muon chambers installed between the inner and middle stations of the forward region and commissioned prior to the 2012 run improve measurements in the transition region of  $1.05 < |\eta| < 1.35$  where the outer stations have no coverage. Muon triggering is possible in the range  $|\eta| < 2.4$ , using resistive-plate chambers in the central region that also provide a mea-

<sup>1</sup>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 along the beam pipe. The  $x$ -axis points from the interaction point to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

surement of the coordinate out of the bending plane, and thin-gap chambers in the forward region. A three-level trigger system [29] selects events to be recorded for offline analysis.

### 3 Simulated event samples

Monte Carlo (MC) simulation samples are used to model the expected signal and background yields, with the exception of certain data-driven background estimates. The MC samples are normalised using the highest-order cross-section predictions available in perturbation theory.

The DY process is generated at next-to-leading order (NLO) using POWHEG [30–33] and the CT10 PDF [34], with PYTHIA 8 [35] to model parton showering and hadronisation. To estimate systematic uncertainties in the event modelling an alternative sample is simulated using the same PDF but the MC@NLO [36–38] generator with HERWIG++ [39]. The  $Z/\gamma^*$  differential cross section as a function of mass has been calculated at next-to-next-to-leading order (NNLO) in perturbative QCD (pQCD) using FEWZ 3.1 [5, 40, 41] with the MSTW2008NNLO PDF [42]. The calculation includes NLO electroweak (EW) corrections beyond final-state photon radiation (FSR). A mass-dependent  $K$ -factor used to scale the  $Z/\gamma^*$  MC sample is obtained from the ratio of the calculated NNLO pQCD cross section with the additional EW corrections, to the cross section from the POWHEG sample. It is found to deviate from unity by 3.5–2.0% across the measured range in  $m_{\ell\ell}$ .

The photon-induced (PI) process,  $\gamma\gamma \rightarrow \ell^+\ell^-$ , is simulated at leading-order using PYTHIA 8 and the MRST2004qed PDF [21]. The MC yield is scaled by a factor of 0.7 in order to match the NLO calculations of SANC [43, 44].

The background from  $t\bar{t}$  production is the dominant background with isolated prompt leptons from electroweak boson decays. It is estimated at NLO using POWHEG and the CT10 PDF, with PYTHIA 6 [45] for parton showering and hadronisation. Two further MC samples for  $t\bar{t}$  and single top ( $Wt$ ) production in association with a  $W$  boson are modelled by MC@NLO and the CT10 PDF, with HERWIG [46, 47] for parton showering and hadronisation. The MC@NLO  $t\bar{t}$  sample is used for estimating systematic uncertainties only. The  $t\bar{t}$  MC samples are normalised to a cross section of  $\sigma_{t\bar{t}} = 253_{-15}^{+13}$  pb for a top-quark mass of 172.5 GeV. This is calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic soft-gluon terms with TOP++2.0 [48–53]. The PDF and  $\alpha_S$  uncertainties on the  $t\bar{t}$  cross section are calculated using the PDF4LHC prescription [54] with the MSTW2008 68% CL NNLO [42, 55], CT10 NNLO [34, 56] and NNPDF2.3 [57] PDF error sets added in quadrature to the scale uncertainty. Varying the top-quark mass by  $\pm 1$  GeV leads to an additional systematic uncertainty of +8 pb and –7 pb, which is also added in quadrature. The single-top background in association with a  $W$  boson has a cross section of  $\sigma_{Wt} = 22.4 \pm 1.5$  pb [58]. Given that the  $Wt$  contribution is small compared to the  $t\bar{t}$  cross section, an overall uncertainty of 6% is estimated on the top-quark background.

Further important background contributions are due to diboson ( $WW$ ,  $WZ$  and  $ZZ$ ) production with decays to final states with at least two leptons. The diboson processes are generated at leading order (LO) with HERWIG, using the CTEQ6L1 PDF [59]. The  $WZ$  and  $ZZ$  cross-section values used are  $20.3 \pm 0.8$  pb and  $7.2 \pm 0.3$  pb respectively, as

| Process    | Generator    | Parton shower  | Generator PDF | Model parameters (“Tune”) |
|------------|--------------|----------------|---------------|---------------------------|
| Drell-Yan  | POWHEG       | PYTHIA 8.162   | CT10          | AU2 [67]                  |
| Drell-Yan  | MC@NLO 4.09  | HERWIG++ 2.6.3 | CT10          | UE-EE-3 [39]              |
| PI         | PYTHIA 8.170 | PYTHIA 8.170   | MRST2004qed   | 4C [68]                   |
| $t\bar{t}$ | POWHEG       | PYTHIA 6.427.2 | CT10          | AUET2 [69]                |
| $t\bar{t}$ | MC@NLO 4.06  | HERWIG 6.520   | CT10          | AUET2                     |
| $Wt$       | MC@NLO 4.06  | HERWIG 6.520   | CT10          | AUET2                     |
| Diboson    | HERWIG 6.520 | HERWIG 6.520   | CTEQ6L1       | AUET2                     |

**Table 1.** Overview of simulated event samples used.

calculated at NLO with MCFM [60, 61] and the CT10 PDF. The  $WW$  cross section is assumed to be  $70.4 \pm 7$  pb, derived by scaling the MCFM value of 58.7 pb by a factor of  $1.20 \pm 0.12$ . This scale factor and its uncertainty correspond to an approximate mean of the two scale factors for  $WW$  production with zero and one extra jet, as discussed in ref. [62]. They are consistent with the recent ATLAS measurement of the  $WW$  cross section at  $\sqrt{s} = 8$  TeV, which yields a value of  $71.1 \pm 1.1$  (stat) $_{-5.0}^{+5.7}$  (sys)  $\pm 1.4$  pb [63].

All MC samples used in the analysis include the effects of FSR, multiple interactions per bunch crossing (“pile-up”), and detector simulation. FSR is simulated using PHOTOS [64], except for samples hadronised by HERWIG++ which includes a native FSR simulation. The effects of pile-up are accounted for by overlaying simulated minimum-bias events [65]. The interactions of particles with the detector are modelled using a full ATLAS detector simulation [65] based on GEANT4 [66]. Finally, several corrections are applied to the simulated samples, accounting for differences between data and simulation in the lepton trigger, reconstruction, identification, and isolation efficiencies as well as lepton resolution and muon momentum scale.

An overview of the simulated event samples is given in table 1.

## 4 Event selection

Events are required to be recorded during stable beam condition periods and must pass detector and data-quality requirements. Due to differences in the detector response to electrons and muons the selection is optimised separately for each channel and is described in the following.

### 4.1 Electron channel

The electron data are collected by a trigger which uses calorimetric information to identify two compact electromagnetic energy depositions. Identification algorithms use calorimeter shower shape information to find candidate electron pairs with a minimum transverse energy of 35 GeV and 25 GeV for the leading and subleading electron. The candidate electron pairs are not matched to inner detector tracks in the trigger allowing the same trigger to be used for the multijet and  $W$ +jets data-driven background estimation studies, where a background-enriched sample is required.

Electrons are reconstructed by clustering energy deposits in the electromagnetic calorimeter using a sliding-window algorithm. These clusters are then matched to tracks reconstructed in the inner detector. The calorimeter provides the energy measurement and the track is used to determine the angular information of the electron trajectory. An energy scale correction determined from  $Z \rightarrow e^+e^-$ ,  $W \rightarrow e\nu$ , and  $J/\psi \rightarrow e^+e^-$  decays [70] is applied to data. Candidates are required to have a pseudorapidity within the inner detector tracking region,  $|\eta^e| < 2.47$ , excluding a region,  $1.37 < |\eta^e| < 1.52$ , where the transition between the barrel and endcap electromagnetic calorimeters is not well modelled in the simulation. Each candidate is required to satisfy the “medium” electron identification [71, 72] criteria based on calorimetric shower shapes and track parameters.

Leptons produced in the Drell-Yan process are expected to be well isolated from energy depositions not associated with the lepton. The degree of isolation for electrons is defined as the scalar sum of transverse energy,  $\sum E_T$ , of additional energy contained in a cone of size  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$  around the electron, omitting the electron transverse energy  $E_T^e$ . This calorimetric isolation is required to satisfy  $\sum E_T(\Delta R = 0.4) < 0.007 \cdot E_T^e + 5$  GeV for the leading electron, and  $\sum E_T(\Delta R = 0.4) < 0.022 \cdot E_T^e + 6$  GeV for the subleading electron, in order to retain a high efficiency of approximately 99% per electron over a large range in  $E_T^e$ .

Candidate events are required to have at least two electrons with  $E_T^e > 30$  GeV and at least one of the electrons satisfying  $E_T^e > 40$  GeV to ensure the selected electron is on the efficiency plateau of the trigger. The invariant mass of the pair is required to be in the range  $116 \leq m_{ee} \leq 1500$  GeV. The absolute difference in pseudorapidity between the two electrons,  $|\Delta\eta_{ee}|$ , is restricted to be less than 3.5 in order to suppress the multijet background which is dominated by  $t$ -channel processes. No charge requirements are placed on the lepton pair due to possible charge misidentification, which can occur either due to bremsstrahlung, or due to the limited momentum resolution of the ID at very high  $p_T$ .

## 4.2 Muon channel

Candidate events in the muon channel are collected using two triggers, each requiring a single muon, but with different transverse momentum thresholds as measured in the higher-level trigger system. A high-threshold trigger demands that the muon transverse momentum be above 36 GeV and collects most of the data sample. A supplementary low-threshold trigger requires an isolated muon with transverse momentum above 24 GeV. The isolation for muons is defined using the scalar sum of transverse momenta,  $\sum p_T$ , of additional tracks divided by  $p_T^\mu$ , the transverse momentum of the muon. This provides a good discriminant against the multijet background arising from the semileptonic decays of heavy quarks. This isolation definition is implemented in the low-threshold trigger in which the candidate muons are required to satisfy  $\sum p_T(\Delta R = 0.2)/p_T^\mu < 0.12$ .

Muons are identified by tracks reconstructed in the muon spectrometer matched to tracks reconstructed in the inner detector and must satisfy  $|\eta^\mu| < 2.4$ . In addition they must pass the “medium” identification criteria [73], based on requirements on the number of hits in the different inner detector and muon spectrometer subsystems, as well as the significance of the charge / momentum ratio imbalance between the ID and MS measure-

ments. Background from multijet events is efficiently suppressed by imposing the isolation condition  $\sum p_T(\Delta R = 0.2)/p_T^\mu < 0.1$ . A small contribution of cosmic-ray muons is removed by requiring the magnitude of the longitudinal impact parameter to the primary interaction vertex,  $z_0$ , to be less than 10 mm. The primary interaction vertex is taken to be the one with the largest sum of squared transverse momenta of all associated tracks.

Events are selected if they contain at least two oppositely charged muons with  $p_T^\mu > 30$  GeV and at least one of the muons satisfies  $p_T^\mu > 40$  GeV in order to have the same phase space as in the electron channel measurement. Finally the dilepton invariant mass is required to be in the range  $116 \leq m_{\mu\mu} \leq 1500$  GeV. No requirement is placed on  $|\Delta\eta_{\mu\mu}|$ .

## 5 Background estimate

The background from processes with two or more isolated final-state leptons of the same flavour is derived from MC simulation. The processes with non-negligible contributions are  $t\bar{t}$ ,  $Wt$  (hereafter termed the top-quark background) and diboson ( $WW$ ,  $WZ$  and  $ZZ$ ) production, see table 1. The background arising from the  $Z/\gamma^* \rightarrow \tau\tau$  process is predicted using MC simulation and found to be negligible.

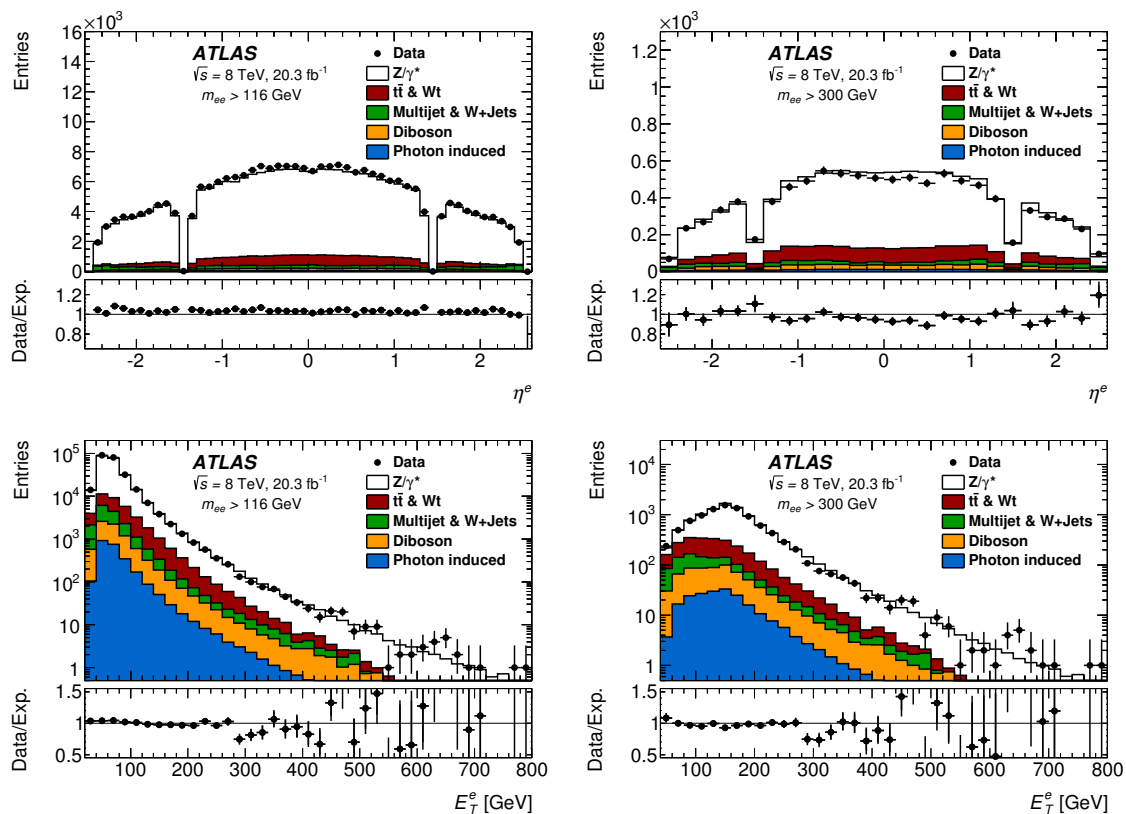
Background contributions from events where at least one final-state jet or photon passes the electron or muon selection criteria are determined using data. This includes contributions from light- and heavy-flavour multijet processes, and  $\gamma + \text{jet}$  production, referred to hereafter as the multijet background. Additional contributions are due to  $W + \text{jets}$  processes and  $t\bar{t}$  and  $Wt$  production with less than two isolated final-state leptons, referred to hereafter as  $W + \text{jets}$  background. The data-driven estimates are described in detail below.

The number of expected events is calculated as the sum of the data-driven and simulated background estimates, and the expected event yield predicted by the DY and PI MC simulations. As can be seen in figures 1–5, good agreement is found in both the  $ee$  and  $\mu\mu$  channels comparing data and expectation for the  $\eta^\ell$  and  $p_T^\ell$  distributions of the leptons, as well as for the distributions in invariant mass, rapidity and  $\Delta\eta_{\ell\ell}$ . The background contributions are stacked in order of increasing importance. In the electron channel the top-quark, multijet and diboson contributions to the expectation are found to be approximately 9%, 4% and 2% respectively in the phase space of the measurement. In the muon channel the top-quark and diboson backgrounds constitute about 9% and 2% of the total expectation, whereas the multijet contribution is below 1% everywhere. The predicted PI contribution is 1% for both channels but can reach as much as 16% in the bin at highest  $m_{\ell\ell}$  and largest  $\Delta\eta_{\ell\ell}$ .

### 5.1 Multijet and $W + \text{jets}$ background estimate in the electron channel

The probability that a jet is misidentified as an electron (the “fake rate”) is determined as a function of transverse energy,  $E_T$  and pseudorapidity,  $\eta$ , of the electron candidate using background-enriched data samples. These samples are recorded using a set of single-jet triggers with  $E_T$  thresholds in the range 25–360 GeV. In each of these samples, the fake rate  $f_1$  ( $f_2$ ) is calculated as the fraction of leading (subleading) electron candidates that pass the nominal electron identification and leading (subleading) electron isolation



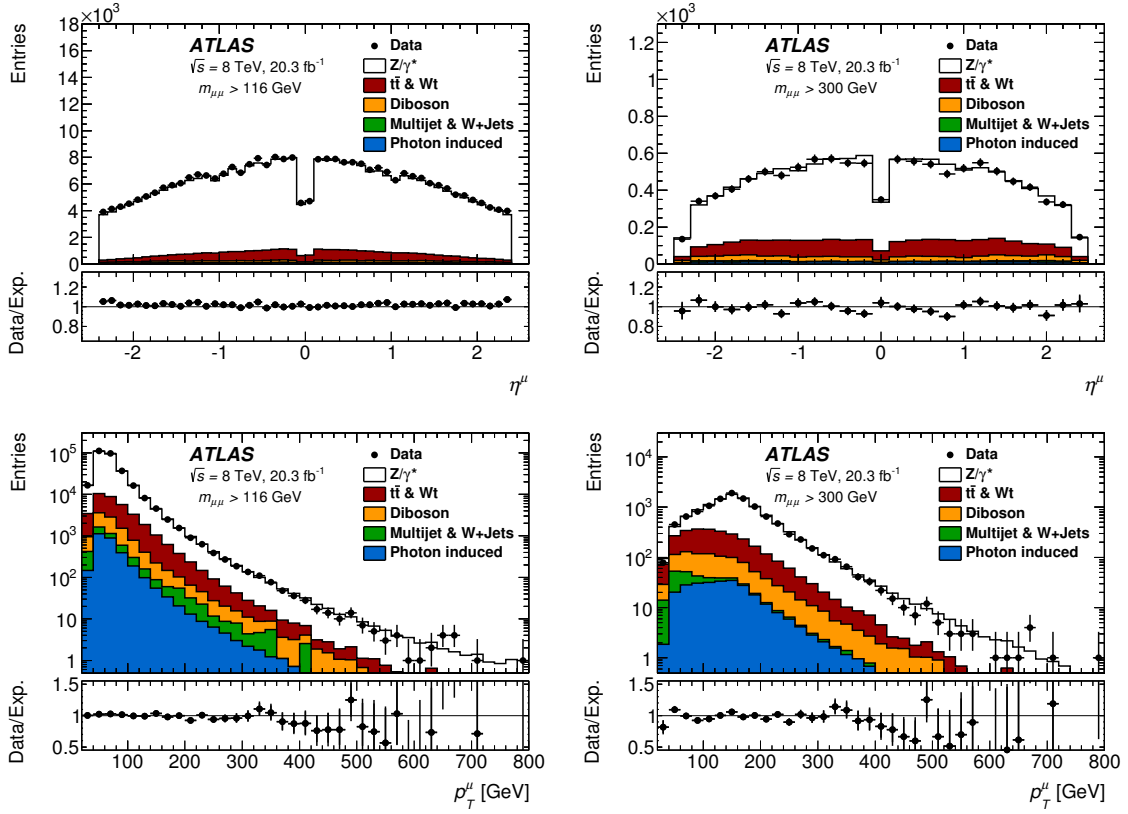


**Figure 1.** Distribution of electron pseudorapidity  $\eta^e$  (upper plots) and transverse energy  $E_T^e$  (lower plots) for invariant masses  $m_{ee} > 116$  GeV (left plots), and  $m_{ee} > 300$  GeV (right plots), shown for data (solid points) and expectation (stacked histogram) after the complete selection. The lower panels show the ratio of data with its statistical uncertainty to the expectation.

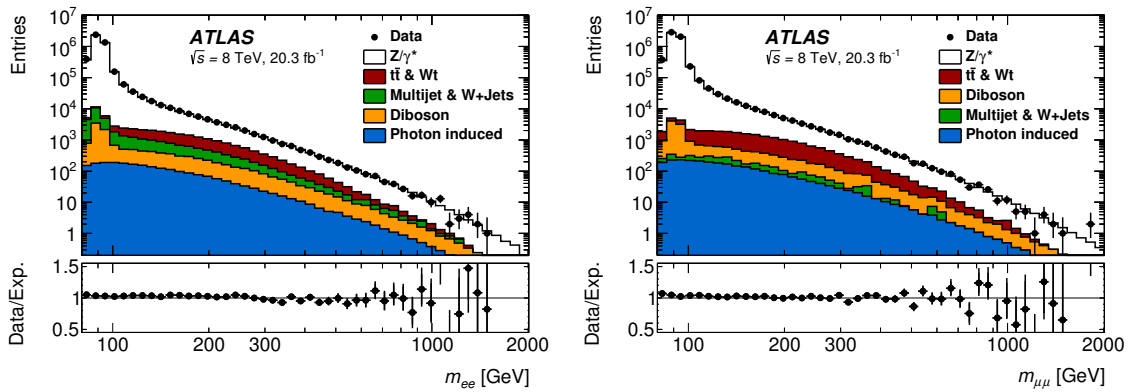
requirements, with respect to the entire sample of “loose” electron candidates. The loose candidates satisfy only a subset of the nominal electron identification criteria. To reject prompt-electron contributions from  $W$  decays or the DY process, events are vetoed in the following cases: if the missing transverse momentum [74] is larger than 25 GeV, if they contain two identified electrons satisfying strict criteria or if they contain two electrons satisfying less strict criteria but with an invariant mass between 71 GeV and 111 GeV. A weighted average of the fake rates obtained from the jet samples is then calculated.

In addition to the fake rate, the probability  $r_1$  ( $r_2$ ) that a prompt electron in this loose selection satisfies the nominal electron identification and leading (subleading) isolation requirements is used in evaluating this background. This probability is taken from the MC simulation as a function of  $E_T$  and  $\eta$ . Potential differences between data and simulated samples in lepton identification and isolation efficiencies are accounted for by applying scale factors [72] to the simulation, which are generally close to unity.

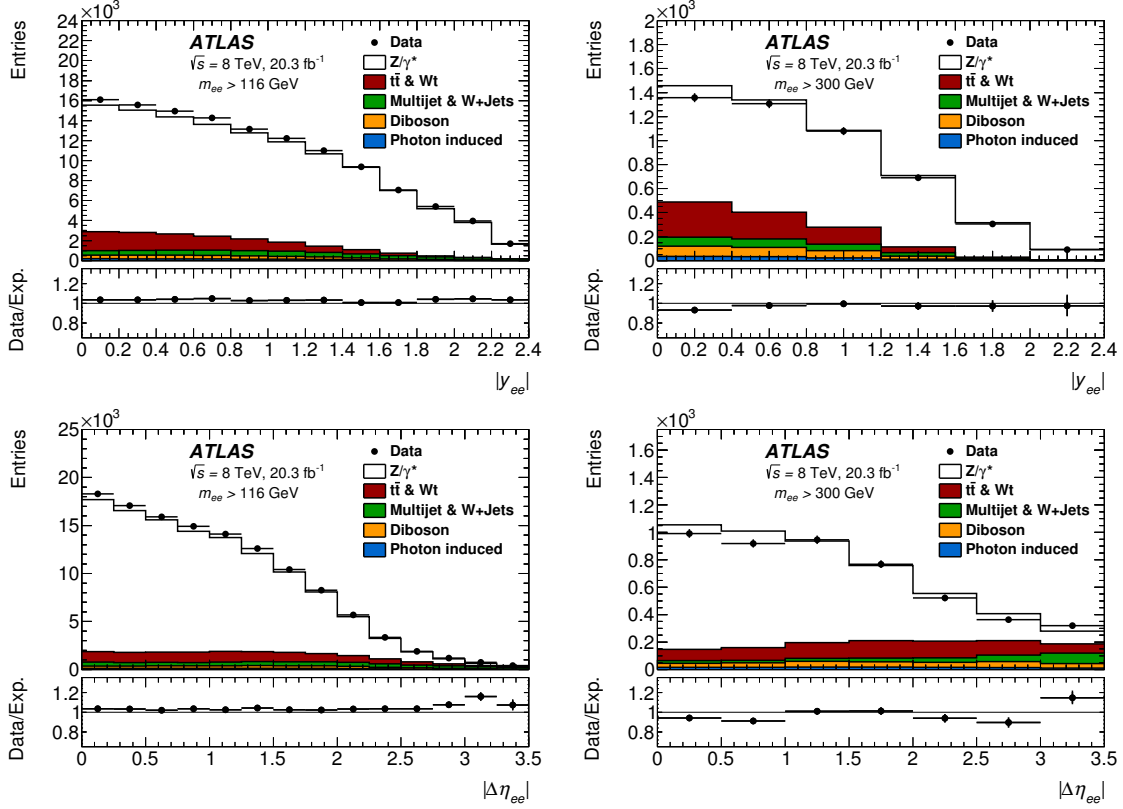
A system of equations is used to solve for the unknown contribution to the background from events with one or more fake electrons in the sample triggered with the default analysis trigger. The relation between the number of true paired objects  $N_{ab}$ , with  $E_T^a > E_T^b$  and



**Figure 2.** Distribution of muon pseudorapidity  $\eta^\mu$  (upper plots) and transverse momentum  $p_T^\mu$  (lower plots) for invariant masses  $m_{\mu\mu} > 116$  GeV (left plots), and  $m_{\mu\mu} > 300$  GeV (right plots), shown for data (solid points) and expectation (stacked histogram) after the complete selection. The lower panels show the ratio of data with its statistical uncertainty to the expectation.



**Figure 3.** The invariant mass ( $m_{\ell\ell}$ ) distribution after event selection for the electron selection (left) and muon selection (right), shown for data (solid points) compared to the expectation (stacked histogram). The lower panels show the ratio of data with its statistical uncertainty to the expectation.



**Figure 4.** Distribution of absolute dielectron rapidity  $|y_{ee}|$  (upper plots) and absolute dielectron pseudorapidity separation  $|\Delta\eta_{ee}|$  (lower plots) for invariant mass  $m_{ee} > 116$  GeV (left plots), and  $m_{ee} > 300$  GeV (right plots), shown for data (solid points) and expectation (stacked histogram) after the complete selection. The lower panels show the ratio of data with its statistical uncertainty to the expectation.

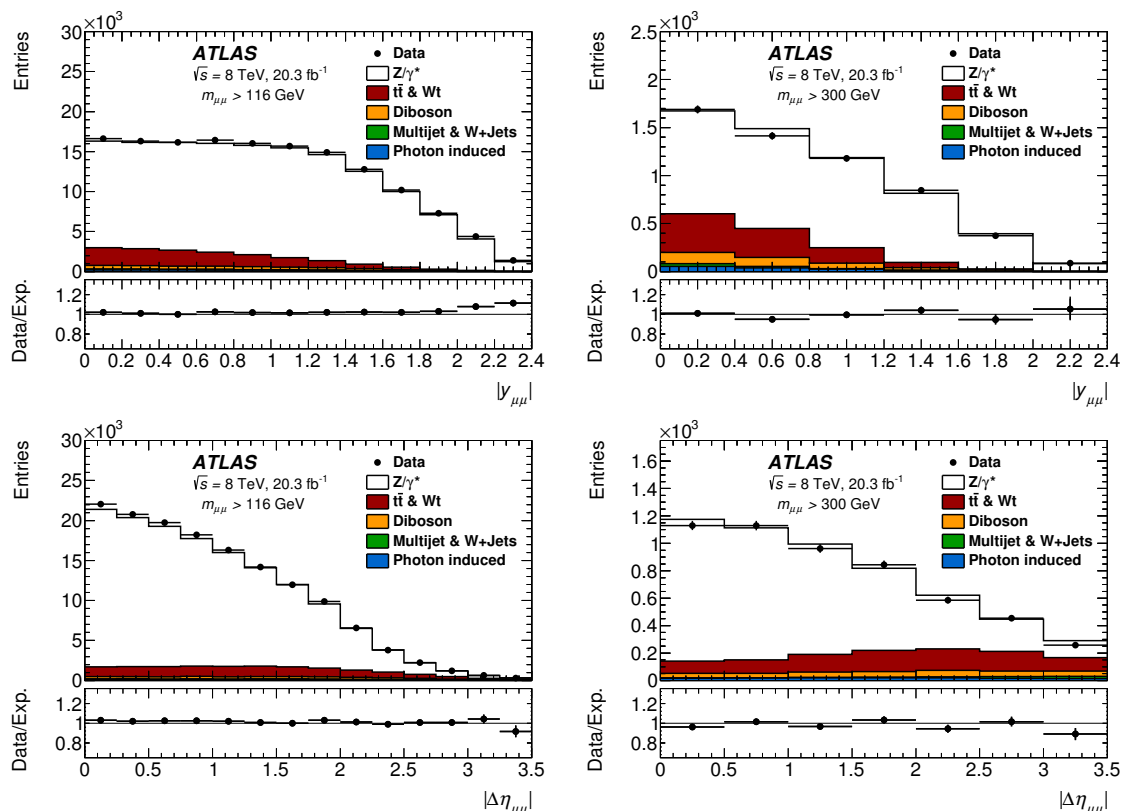
$a, b \in \{R, F\}$ , and the number of measured pairs  $N_{xy}$ , with  $x, y \in \{T, L\}$ , can be written as:

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}. \quad (5.1)$$

The subscripts  $R$  and  $F$  refer to prompt electrons and fake electrons (jets) respectively. The subscript  $T$  refers to electrons that pass the nominal selection. The subscript  $L$  corresponds to electrons that pass the loose requirements described above but fail the nominal requirements.

The background originating from pairs of objects with at least one fake electron ( $N_{TT}^{\text{Multijet}\&W+\text{jets}}$ ) in the total number of pairs, where both objects are reconstructed as signal-like (i.e. contribute to  $N_{TT}$ ) is given by:

$$N_{TT}^{\text{Multijet}\&W+\text{jets}} = r_1 f_2 N_{RF} + f_1 r_2 N_{FR} + f_1 f_2 N_{FF}. \quad (5.2)$$



**Figure 5.** Distribution of absolute dimuon rapidity  $|y_{\mu\mu}|$  (upper plots) and absolute dimuon pseudorapidity separation  $|\Delta\eta_{\mu\mu}|$  (lower plots) for invariant mass  $m_{\mu\mu} > 116$  GeV (left plots), and  $m_{\mu\mu} > 300$  GeV (right plots), shown for data (solid points) and expectation (stacked histogram) after the complete selection. The lower panels show the ratio of data with its statistical uncertainty to the expectation.

The number of true paired objects on the right-hand side of equation (5.2) can be expressed in terms of measurable quantities ( $N_{TT}$ ,  $N_{TL}$ ,  $N_{LT}$ ,  $N_{LL}$ ) by inverting the matrix in equation (5.1). The normalisation and shape of the background in each variable of interest are automatically derived by using the measurable quantities as a function of that same variable. The estimated multijet background over the full invariant mass range is found to be about 3%.

## 5.2 Multijet and $W$ +jets background estimate in the muon channel

The multijet background remaining after the complete event selection in the muon channel is largely due to heavy flavour  $b$ - and  $c$ -quark decays, and is estimated using a data-driven technique in two s-eps-converted-to.pdf. This method also accounts for any potential  $W$ +jets background, however, the contribution of this component is expected to be negligible. First the normalisation of the multijet background in each  $m_{\mu\mu}$  bin is determined, and then the shape in the  $|y_{\mu\mu}|$  and in  $|\Delta\eta_{\mu\mu}|$  variables is estimated.

The background in each invariant mass region is determined using three orthogonal control regions with inverted muon isolation requirements, and/or inverted muon-pair

charge requirements. The two variables are largely uncorrelated for the multijet background. In each control region the contamination from signal, top-quark, and diboson background is subtracted using simulation. The yield of multijet events in the signal region is predicted using the constraint that the yield ratio of opposite-charge to same-charge muon pairs is identical in the isolated and non-isolated regions. A comparison of the isolation distribution for muons in events with either same-charge and opposite-charge muon pairs shows a small linear deviation of up to 10% when extrapolated into the isolated signal region. This is found to be independent of  $m_{\mu\mu}$ , and is corrected for. For the region  $m_{\mu\mu} > 500$  GeV there are insufficient same-charge isolated muon pairs to give a reliable estimate. Therefore, the background yield in the region  $m_{\mu\mu} < 500$  GeV is fitted to two alternative functional forms and extrapolated to larger  $m_{\mu\mu}$  where the averaged prediction is taken as the estimate of the background yield. The  $|y_{\mu\mu}|$  and  $|\Delta\eta_{\mu\mu}|$  dependence of the background in each  $m_{\mu\mu}$  region is obtained from a multijet-enriched data control region in which pairs of same-charge and opposite-charge muons satisfy  $\sum p_T(\Delta R = 0.2)/p_T^\mu > 0.1$ . Signal, top-quark and diboson contamination in this control region is subtracted using MC simulation. The resulting  $|y_{\mu\mu}|$  and  $|\Delta\eta_{\mu\mu}|$  spectra in each  $m_{\mu\mu}$  region are normalised to the yield obtained in the first step. For  $m_{\mu\mu} > 500$  GeV the  $|y_{\mu\mu}|$  or  $|\Delta\eta_{\mu\mu}|$  shape is taken from the region  $300 < m_{\mu\mu} < 500$  GeV. Overall the total multijet background varies from 1% to 0.1% over the complete invariant mass range.

## 6 Cross-section measurement

The Drell-Yan cross section, including the irreducible contribution from the PI process, is measured differentially in 12 bins of  $m_{\ell\ell}$  from 116 GeV to 1500 GeV, as well as double-differentially in five bins of  $m_{\ell\ell}$  as a function of  $|y_{\ell\ell}|$  and  $|\Delta\eta_{\ell\ell}|$ . The results are presented in the fiducial region of the measurement, in which the leading (subleading) lepton has a  $p_T^\ell > 40$  GeV ( $p_T^\ell > 30$  GeV) and both leptons are within  $|\eta^\ell| < 2.5$ . The kinematic variables are defined by the leptons before FSR, i.e. the results are given at the Born-level in QED. Results at the “dressed” level, where leptons after FSR are recombined with radiated photons within a cone of  $\Delta R = 0.1$ , are obtained by multiplying the Born-level results with the dressed correction factors  $k_{\text{dressed}}$ , provided in tables 6–11 in the appendix. These correction factors are obtained from the POWHEG and PYTHIA 8 MC samples for the DY and PI processes, respectively.

The double-differential cross section as a function of invariant mass and rapidity is calculated as

$$\frac{d^2\sigma}{dm_{\ell\ell} d|y_{\ell\ell}|} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{\text{DY}} \mathcal{L}_{\text{int}}} \frac{1}{\Delta_{m_{\ell\ell}} 2\Delta_{|y_{\ell\ell}|}}, \quad (6.1)$$

where  $N_{\text{data}}$  is the number of candidate events observed in a given bin of  $m_{\ell\ell}$  and  $|y_{\ell\ell}|$  of width  $\Delta_{m_{\ell\ell}}$  and  $\Delta_{|y_{\ell\ell}|}$  respectively. The total background in that bin is denoted as  $N_{\text{bkg}}$  and  $\mathcal{L}_{\text{int}}$  is the integrated luminosity. The factor of two in the denominator accounts for the modulus in the rapidity bin width. The double-differential cross section as a function of mass and  $|\Delta\eta_{\ell\ell}|$  and the single-differential measurement as a function of invariant mass are defined accordingly.

The factor,  $C_{\text{DY}}$ , takes into account the efficiency of the signal selection and bin migration effects. It is defined as the number of MC generated events that pass the signal selection in a certain measurement bin calculated from the reconstructed lepton kinematics divided by the total number of generated events within the fiducial region, in the corresponding bin, calculated from Born-level or dressed-level lepton kinematics. It is obtained from the Drell-Yan and PI MC samples after correction for differences in the reconstruction, identification, trigger, and isolation efficiencies between data and simulation, as well as for momentum scale and resolution mismodelling effects. In general the  $C_{\text{DY}}$  factors are found to be in the range 60–80% across the measured kinematic range.

The  $C_{\text{DY}}$  factor also includes extrapolations over the small regions that are excluded for reconstructed electron ( $1.37 < |\eta^e| < 1.52$  and  $2.47 < |\eta^e| < 2.5$ ) or muon ( $2.4 < |\eta^\mu| < 2.5$ ) candidates. In the electron channel, the fiducial cross section measurements as a function of  $m_{ee}$  and  $|y_{ee}|$ , and the single-differential measurement, are extrapolated over the unmeasured region  $|\Delta\eta_{ee}| > 3.5$ . The extrapolation correction is included in the  $C_{\text{DY}}$  factor. No such extrapolation is required for the double-differential measurement as function of mass and  $|\Delta\eta_{ee}|$  which only extends to  $|\Delta\eta_{ee}| = 3$ .

The Born-level bin purity is defined as the fraction of reconstructed MC signal events in a given bin which were also generated in the same bin using Born-level lepton kinematics. An analogous definition is used for the dressed-level bin purity. The bin purities are found to be typically above 85%, and above 75% everywhere. This ensures that the bin migration effects are small, and the corrections applied to account for bin migrations have small uncertainties.

## 7 Systematic uncertainties

The systematic uncertainties on the measurements are discussed separately for those sources which arise only in the electron channel, those which arise only in the muon channel, and those which are common to both measurements. In each section the sources are discussed in order of importance, with the largest sources of uncertainty listed first. Each source is classified as being correlated or uncorrelated between measurement bins in a single channel. The uncorrelated sources are propagated using the pseudo-experiment method in which the correction factors used to improve the modelling of data by the simulation are randomly shifted in an ensemble of pseudo-experiments according to the mean and standard deviation of the correction factor. The resulting uncertainty on the measured cross section is determined from the variance of the measurements for the ensemble. The correlated contributions are propagated by the offset method in which the values from each source are coherently shifted upwards and downwards by one standard deviation and the magnitude of the change in the measurement is computed. The sign of the uncertainty corresponds to a one standard deviation upward shift of the uncertainty source.

### 7.1 Electron channel

The systematic uncertainties on the cross section that are unique to the electron channel are dominated by the uncertainties in the determination of the multijet and  $W$ +jets

background described in section 5.1, and in the electron energy scale. In addition, a large contribution to the uncertainty also arises from the top-quark and diboson background subtraction, and is discussed in section 7.3.

All correlated and uncorrelated contributions to the systematic uncertainties are given in each bin of the measurement in tables 6, 7, and 8 of the appendix.

### 7.1.1 Multijet and $W$ +jets background

In order to derive the uncertainty on the data-driven background estimate described in section 5.1, the default “matrix method” is altered by assuming  $r_1 = r_2 = 1$ . This second matrix method leads to a simplification of the matrix in equation (5.1), but also necessitates the use of MC corrections to account for the identification and isolation inefficiencies of real electrons. Large MC corrections can be avoided in a third matrix method where the contamination from real electrons is reduced. The subscript  $L$  in equation (5.1) now corresponds to electrons that pass the loose requirements but fail the requirement on the matching between track and cluster, instead of failing the full identification and isolation requirements.

In addition, two alternative background-enriched samples are obtained using a tag-and-probe technique on the jet-triggered sample and on the sample triggered by the default analysis triggers, requiring the tag to fail certain aspects of the electron identification depending on the trigger. Furthermore, the event should have a missing transverse momentum smaller than 25 GeV, the probe needs to have the same charge as the tag and the invariant mass of the tag-and-probe pair needs to be outside the  $Z$  mass window from 71 to 111 GeV.

The default and the two additional matrix methods are each used in conjunction with the default and the two alternative background-enriched samples, leading to a default and eight alternative background estimates. Out of the eight alternative background estimates those two are identified that in general, i.e. in almost all bins except for fluctuations, yield the largest and smallest background contribution. In each bin, the average absolute difference between those two and the default background estimate is used as a systematic uncertainty on the method.

Another systematic uncertainty can arise if fake rates are different for the various processes contributing to this background, and if the relative contributions of these processes differ between the data samples from which the fake rates are measured and the data sample to which the fake rates are applied. For example, jets originating from bottom quarks have a higher fake rate than light-quark jets, but the effect of this is negligible as the number of  $b$ -jets is small and similar in both samples. However, as an additional check the background is recalculated using all nine methods discussed above, but with separate fake rates for different background processes. As the mean of these nine methods is in agreement with the default background estimate no additional systematic uncertainty is applied.

The uncertainty on the default fake-rate calculation is derived by varying the requirements used to suppress real electron contamination in the data sample used to measure the fake rate. The largest deviation of about 5% on the background occurs when the value of the missing transverse energy requirement is changed. It is added in quadrature to the systematic uncertainty on the method to obtain the full systematic uncertainty ( $\delta_{\text{cor}}^{\text{mult.}}$ ) on

the cross section that is correlated between bins. The value of  $\delta_{\text{cor}}^{\text{mult.}}$  is found to be around 1%, rising to almost 4% at large  $|\Delta\eta_{ee}|$ .

The uncorrelated part consists of the statistical uncertainty on the fake rates, which results in an uncertainty on the background of at most 5%, and of the statistical uncertainty from the sample to which the fake rates are applied. These two sources are added in quadrature and yield the uncertainty ( $\delta_{\text{unc}}^{\text{mult.}}$ ) on the cross section that is uncorrelated between bins and is typically less than 0.5%, increasing to 3% at large  $|\Delta\eta_{ee}|$ .

### 7.1.2 Energy scale and resolution

The electron energy scale and resolution as well as the corresponding uncertainties are determined using  $Z \rightarrow e^+e^-$ ,  $W \rightarrow e\nu$ , and  $J/\psi \rightarrow e^+e^-$  decays [70]. The uncertainty on the energy scale is separated into 14 uncorrelated systematic sources as well as one statistical component. The statistical uncertainty on the energy scale is found to be negligible. Adding the effects of the 14 sources of uncertainty on the energy scale in quadrature after propagating to the measured cross sections, the combined uncertainty is denoted as  $\delta_{\text{cor}}^{\text{Escale}}$ , and is 1–4% for  $m_{ee} > 200$  GeV, but is better than 0.5% at lower  $m_{ee}$  and central rapidity.

The uncertainty on the energy resolution is separated into seven uncorrelated systematic sources which are propagated to the cross-section measurements individually and then quadratically summed. This combined uncertainty is denoted as  $\delta_{\text{cor}}^{\text{Eres}}$  and is typically 0.1–0.2% everywhere except at large  $|y_{ee}|$  or large  $|\Delta\eta_{ee}|$ .

### 7.1.3 Reconstruction, identification and isolation efficiency

The reconstruction and identification efficiencies of electrons are determined from data for electrons with  $E_{\text{T}}^e$  up to about 100 GeV, using various tag-and-probe methods in  $Z$  and  $J/\psi$  decays, following the prescription of ref. [71] with certain improvements and adjustments for the 2012 conditions [72]. In order to extend the measurement range of the identification efficiency, the tag-and-probe method using the isolation distribution of the probe for the discrimination between signal and background in  $Z \rightarrow e^+e^-$  decays [72] is carried out up to about 500 GeV in  $E_{\text{T}}^e$ . Within statistical uncertainties, the identification efficiencies are found to be stable and consistent with the one derived in the last bin ( $E_{\text{T}}^e < 80$  GeV) in ref. [72].

The differences between the measured reconstruction and identification efficiencies and their values in MC simulation are taken as  $\eta$ - and  $E_{\text{T}}$ -dependent scale factors with which the  $C_{\text{DY}}$  factor derived from simulation is corrected. Similarly, scale factors for the isolation requirements on the leading and subleading electron are derived using a tag-and-probe method in  $Z \rightarrow e^+e^-$  decays. They are applied as a function of  $E_{\text{T}}^e$  only, as the  $\eta$  dependence is negligible.

The uncertainties on the cross section due to the systematic uncertainties on the scale factors for the electron reconstruction, identification and isolation as well as the statistical uncertainty on the isolation are denoted as  $\delta_{\text{cor}}^{\text{reco}}$ ,  $\delta_{\text{cor}}^{\text{id}}$ ,  $\delta_{\text{cor}}^{\text{iso}}$  and  $\delta_{\text{unc}}^{\text{iso}}$  respectively. Of these, the largest component is  $\delta_{\text{cor}}^{\text{id}}$ , which is found to be 0.5–1% everywhere. The uncertainty  $\delta_{\text{cor}}^{\text{reco}}$  is generally below 0.3% and better than 1% everywhere. Both components of the isolation efficiency uncertainty are found to be 0.2% or better for  $m_{ee} < 300$  GeV.



### 7.1.4 Trigger efficiency

The trigger efficiency is measured in data and in the MC simulation using a tag-and-probe method in  $Z \rightarrow e^+e^-$  decays. The differences as a function of  $E_T^e$  are found to be smaller than 1% everywhere, with no dependence on  $\eta$ . Therefore,  $E_T^e$ -dependent scale factors are used to correct  $C_{DY}$ . The uncertainty on the cross section due to the statistical ( $\delta_{\text{unc}}^{\text{trig}}$ ) and systematic ( $\delta_{\text{cor}}^{\text{trig}}$ ) uncertainties on the trigger efficiency are each found to be 0.1% or better for  $m_{ee} < 300$  GeV.

## 7.2 Muon channel

Uncertainties related to the muon trigger, reconstruction, isolation and impact parameter efficiencies, as well as the muon momentum scale and resolution are all studied using the  $Z \rightarrow \mu^+\mu^-$  process and a tag-and-probe method. Of these, the largest contribution to the measurement precision arises from the reconstruction efficiency modelling, and the muon momentum scale calibration. However, the top-quark and diboson background subtraction is also a dominant source of uncertainty, and is discussed in section 7.3. A detailed breakdown of the uncertainties is provided in tables 9, 10 and 11 in the appendix.

### 7.2.1 Reconstruction efficiency

This is the dominant source of muon-related correlated systematic uncertainty and is dominated at large  $p_T^\mu$  by the uncertainty in contributions from catastrophic muon energy loss via bremsstrahlung [73]. When propagated to the cross section this source is found to be typically 0.5%, rising to 1% at the highest  $p_T^\mu$ . This contribution is denoted as  $\delta_{\text{cor}}^{\text{reco}}$ .

### 7.2.2 Momentum scale and resolution

The corrections on muon momentum scale and resolution are obtained from fits to the  $Z \rightarrow \mu^+\mu^-$  line-shape with scale and resolution parameters in local  $\eta^\mu$  and  $\phi^\mu$  regions, separately for muon tracks reconstructed in the ID and the MS [73]. Uncertainties arising from the methodology result in a correlated systematic uncertainty on the measured cross sections of typically 0.4%. These contributions are listed as  $\delta_{\text{cor}}^{\text{pT}}$  for the momentum scale, and  $\delta_{\text{cor}}^{\text{MSres}}$  and  $\delta_{\text{cor}}^{\text{IDres}}$  for the MS and ID resolution uncertainties respectively.

### 7.2.3 Isolation and impact parameter efficiency

Modelling of the muon isolation and impact parameter selection efficiencies can give rise to additional systematic uncertainties and are estimated together. The sources considered include the remaining background contamination, the residual variation in  $\eta^\mu$ , and a possible bias from the event topology estimated by varying the azimuthal opening angle between the two muons used in the tag-and-probe method. The resulting correlated cross-section uncertainty is found to be typically 0.1%, rising to 0.5% at large  $m_{\mu\mu}$ . This contribution is labelled as  $\delta_{\text{cor}}^{\text{iso}}$ .

### 7.2.4 Multijet and $W$ +jets background

The uncertainty on the multijet background estimation consists of several sources. The statistical uncertainty of the control regions is propagated in the appropriate way and can

be significant, in particular from the isolated same-sign control sample. The subtracted top-quark and diboson contamination in the control regions is varied within the theoretical cross section uncertainties given in section 3. The subtracted signal contamination is varied by  $\pm 5\%$ . The extrapolation uncertainty in the multijet estimate at large invariant mass is estimated taking half the difference between the two extrapolation functions and is the largest contribution to the uncertainty in this region. The uncertainty in the shape of the  $|y_{\mu\mu}|$  and  $|\Delta\eta_{\mu\mu}|$  spectra is determined from the RMS of these distributions in regions of small, moderate and large non-isolation of the muon pairs obtained from the control regions. This component typically dominates the uncertainty at large  $|y_{\mu\mu}|$  and small  $|\Delta\eta_{\mu\mu}|$ . These sources are combined into correlated and uncorrelated components, where the latter is due to the statistical uncertainty of the method, and are denoted as  $\delta_{\text{cor}}^{\text{mult.}}$  and  $\delta_{\text{unc}}^{\text{mult.}}$ . The combined uncertainty in the background estimation ranges from 20% at low  $m_{\mu\mu}$  to above 100% at the highest  $m_{\mu\mu}$ , however when propagated onto the cross section measurements it is below 1% in all double differential measurement bins.

### 7.2.5 Trigger efficiency

The trigger efficiency corrections obtained using the tag-and-probe method as described in ref. [75] are parameterised in terms of muon pseudorapidity  $\eta^\mu$ , azimuthal angle  $\phi^\mu$ , and electric charge. The uncertainty sources considered are the background contamination, a possible residual dependence on muon  $p_T^\mu$ , and an uncertainty based on the event topology. This results in a correlated uncertainty on the measured cross sections of 0.1% and is denoted as  $\delta_{\text{cor}}^{\text{trig}}$ .

## 7.3 Systematic uncertainties common to both channels

The systematic uncertainties common to both channels are derived using identical methods and are assumed to be fully correlated between the channels. They are dominated by the uncertainty on the  $t\bar{t}$  background and the luminosity. The statistical uncertainties of the MC samples used are uncorrelated between the measurement channels.

### 7.3.1 Top and diboson background

In most of the phase space the largest background in both the electron and the muon channel is due to top-quark production. The normalisation uncertainty on this background is taken to be 6% as already described in section 3. The top-quark background is dominated by  $t\bar{t}$  production, which is modelled using two different MC generators, see table 1. No systematic differences have been found when comparing the distributions in dilepton invariant mass, rapidity and  $\Delta\eta$ . Another important background is due to diboson ( $WW$ ,  $WZ$  and  $ZZ$ ) production. The normalisation uncertainties are about 10% (see section 3).

To further validate the normalisation and shape of the  $t\bar{t}$  and diboson simulations used in this analysis, a data control region is defined by an opposite-charge electron-muon pair selection that is chosen to match the nominal muon and electron pair selections as closely as possible. This selection strongly suppresses the Drell-Yan process and leads to a sample with about an 80% contribution from top-quark production at lower invariant masses, decreasing to about 50% for the highest masses. The remaining events are mainly due to

diboson production. As no systematic differences are found comparing dilepton invariant mass, rapidity and  $\Delta\eta$  distributions in data and simulation no further uncertainties are assigned. The normalisation uncertainties of the top ( $\delta_{\text{cor}}^{\text{top}}$ ) and diboson ( $\delta_{\text{cor}}^{\text{diboson}}$ ) backgrounds as well as the statistical uncertainty of both simulations combined ( $\delta_{\text{unc}}^{\text{bgMC}}$ ) are given in the appendix.

### 7.3.2 Luminosity

The uncertainty on the integrated luminosity is 1.9%, which is derived by following the methodology detailed in ref. [76].

### 7.3.3 MC statistics and MC modelling

The bin-by-bin correction factor  $C_{\text{DY}}$  is calculated from the Drell-Yan and PI MC samples as already described in section 6. In order to check for a potential model dependence, two different Drell-Yan samples are generated, see table 1, and no systematic differences have been found for  $C_{\text{DY}}$  as a function of invariant mass, rapidity and  $\Delta\eta$ . Similarly, a negligible influence on these distributions is found when assigning a 40% uncertainty to the cross section of the PI MC sample. This value is derived by calculating the PI contribution in a constituent and a current quark mass scheme [21], and taking the magnitude of the difference between either scheme and their average [7]. The statistical uncertainty due to the finite number of signal MC events used in the calculation of  $C_{\text{DY}}$  is denoted as  $\delta_{\text{unc}}^{\text{MC}}$ .

### 7.3.4 Bin-by-bin correction

The bin-by-bin correction used in the calculation of the cross section is compared to an iterative Bayesian unfolding technique [77] as implemented in the program RooUnfold [78]. The differences between these two approaches are found to be negligible.

### 7.3.5 PDF uncertainty

As discussed in section 6, the  $C_{\text{DY}}$  correction factor also includes a small extrapolation from the measured region to the fiducial region. This acceptance correction is about 13% for electrons and 5% for muons, but can be larger in certain bins of the two-dimensional cross-section measurement. The PDF uncertainties due to the acceptance correction are estimated using the CT10 PDF eigenvector set at 68% confidence level (CL). They are found to be negligible, with uncertainties of the order of 0.1% or below for most cross-section measurement bins, and below 0.2% everywhere.

## 8 Results

The measured Born-level fiducial cross sections for the electron and muon channel analyses are in good agreement with one another and each achieve a precision of 1% at low  $m_{\ell\ell}$  where they are dominated by the experimental systematic uncertainties. For  $m_{\ell\ell} \gtrsim 400$  GeV the statistical uncertainty of the data samples dominates the measurement precision. The

measurements are presented in tables 6–11 of the appendix, including the systematic uncertainties (excluding the luminosity measurement uncertainty) separated into those which are point-to-point correlated and those which are uncorrelated.

The two measurement channels are defined with a common fiducial region given in section 6, therefore, they can be combined to further reduce the statistical uncertainty. A further reduction in the total uncertainty is also achieved by taking into account systematic uncertainties which are not correlated between the two measurement channels. A  $\chi^2$  minimisation technique is used to perform the combination of the cross sections [79–81]. This method introduces a free nuisance parameter for each correlated systematic error source which contributes to the total  $\chi^2$ , and therefore gives results that are different from a simple weighted average. The combination is performed separately for each differential cross-section measurement. The sources of uncertainty considered are discussed in section 7, some of which consist of several contributions. However, for ease of presentation only the major sources are reported in tables 6–11 giving a total of 35 nuisance parameters. Only the normalisation uncertainties of the  $t\bar{t}$  and diboson backgrounds are correlated between the channels, using two common nuisance parameters. After the minimisation, no nuisance parameter is shifted by more than one standard deviation. The  $\chi^2$  per degree of freedom,  $\chi^2/dof$ , is found to be  $14.2/12 = 1.19$  for the single-differential cross section,  $53.1/48 = 1.11$  for the cross sections differential in  $m_{\ell\ell}$  and  $|y_{\ell\ell}|$ , and  $59.3/47 = 1.26$  for the cross sections differential in  $m_{\ell\ell}$  and  $|\Delta\eta_{\ell\ell}|$ .

The combined fiducial cross sections are presented in tables 2, 3 and 4. The combination procedure yields orthogonal systematic uncertainty sources, as listed in the tables, which are formed of linear combinations of the original uncertainties. The combined cross sections have an improved precision across the kinematic range, where at low  $m_{\ell\ell}$  an accuracy of better than 1% is attained. The double-differential cross sections have an accuracy of between 1% and 7% throughout the kinematic range of the measurements.

The results of the combination are shown in figures 6–8. In each figure the upper panels show the measured Born-level cross sections for the electron channel, muon channel and the combination. The ratio of the individual channels to the combined measurement is also shown as well as the pulls from the two channels, defined as the single-channel measurement subtracted from the combined result in units of the uncertainty. No coherent trends between the measurements are observed and the pulls are found to be typically below two standard deviations, and everywhere below three standard deviations.

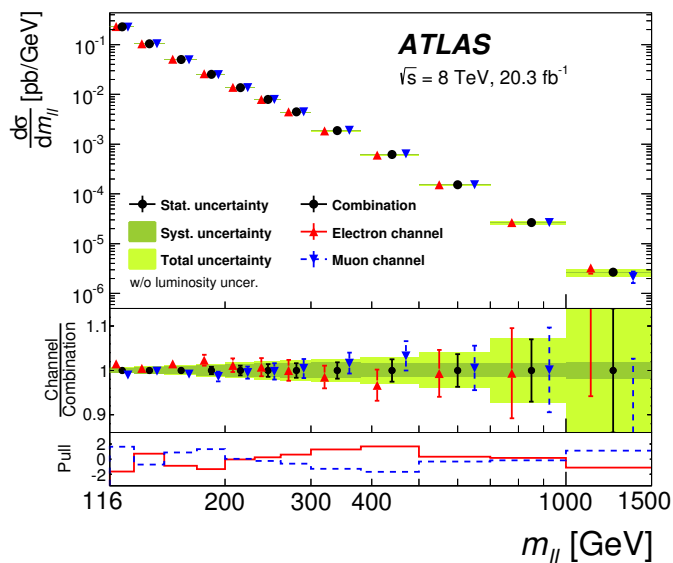
The single-differential cross section shown in figure 6 falls rapidly over five orders of magnitude as  $m_{\ell\ell}$  increases by about a factor of ten. In figure 7 the cross sections differential in  $m_{\ell\ell}$  and  $|y_{\ell\ell}|$  show a marked narrowing of the rapidity plateau width as  $m_{\ell\ell}$  increases. The measurements obtained as a function of  $|\Delta\eta_{\ell\ell}|$  and  $m_{\ell\ell}$  are shown in figure 8. For all  $m_{\ell\ell}$ , the cross sections are largest where the absolute magnitude of the lepton pseudorapidity separation is close to zero, and are observed to fall as the separation increases.

| $m_{\tilde{t}_2}$<br>[GeV] | $\frac{d\sigma}{dm_{\tilde{t}_2}}$<br>[pb/GeV] | $\delta^{\text{stat}}$<br>[%] | $\delta^{\text{sys}}$<br>[%] | $\delta^{\text{unc}}$<br>[%] | $\delta_{\text{cor}}^1$<br>[%] | $\delta_{\text{cor}}^2$<br>[%] | $\delta_{\text{cor}}^3$<br>[%] | $\delta_{\text{cor}}^4$<br>[%] | $\delta_{\text{cor}}^5$<br>[%] | $\delta_{\text{cor}}^6$<br>[%] | $\delta_{\text{cor}}^7$<br>[%] | $\delta_{\text{cor}}^8$<br>[%] | $\delta_{\text{cor}}^9$<br>[%] | $\delta_{\text{cor}}^{10}$<br>[%] | $\delta_{\text{cor}}^{11}$<br>[%] | $\delta_{\text{cor}}^{12}$<br>[%] | $\delta_{\text{cor}}^{13}$<br>[%] | $\delta_{\text{cor}}^{14}$<br>[%] | $\delta_{\text{cor}}^{15}$<br>[%] | $\delta_{\text{cor}}^{16}$<br>[%] | $\delta_{\text{cor}}^{17}$<br>[%] | $\delta_{\text{cor}}^{18}$<br>[%] | $\delta_{\text{cor}}^{19}$<br>[%] | $\delta_{\text{cor}}^{20}$<br>[%] | $\delta_{\text{cor}}^{21}$<br>[%] | $\delta_{\text{cor}}^{22}$<br>[%] | $\delta_{\text{cor}}^{23}$<br>[%] | $\delta_{\text{cor}}^{24}$<br>[%] | $\delta_{\text{cor}}^{25}$<br>[%] | $\delta_{\text{cor}}^{26}$<br>[%] | $\delta_{\text{cor}}^{27}$<br>[%] | $\delta_{\text{cor}}^{28}$<br>[%] | $\delta_{\text{cor}}^{29}$<br>[%] | $\delta_{\text{cor}}^{30}$<br>[%] | $\delta_{\text{cor}}^{31}$<br>[%] | $\delta_{\text{cor}}^{32}$<br>[%] | $\delta_{\text{cor}}^{33}$<br>[%] | $\delta_{\text{cor}}^{34}$<br>[%] | $\delta_{\text{cor}}^{35}$<br>[%] |       |       |
|----------------------------|--|-------------------------------|------------------------------|------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-------|-------|
| 116-130                    | $2.28 \times 10^{-1}$                          | 0.34                          | 0.53                         | 0.63                         | 0.12                           | 0.24                           | -0.01                          | 0.08                           | -0.03                          | -0.03                          | 0.00                           | 0.01                           | 0.01                           | 0.00                              | 0.01                              | 0.00                              | 0.00                              | 0.00                              | 0.00                              | -0.01                             | -0.00                             | 0.01                              | -0.00                             | 0.01                              | -0.02                             | 0.01                              | -0.02                             | -0.05                             | -0.31                             | 0.15                              | 0.18                              | 0.03                              | -0.04                             | -0.01                             | -0.02                             | 0.11                              | 0.04                              | 0.07                              | 0.07                              | 0.09  | -0.05 |
| 130-150                    | $1.04 \times 10^{-1}$                          | 0.44                          | 0.67                         | 0.80                         | 0.13                           | 0.38                           | -0.00                          | 0.03                           | -0.05                          | -0.02                          | 0.03                           | 0.00                           | 0.01                           | 0.00                              | 0.00                              | 0.00                              | 0.00                              | 0.00                              | 0.00                              | -0.01                             | -0.01                             | -0.01                             | 0.02                              | 0.01                              | 0.01                              | 0.08                              | -0.08                             | -0.38                             | 0.10                              | 0.15                              | 0.04                              | -0.08                             | 0.01                              | 0.04                              | 0.22                              | 0.03                              | 0.08                              | 0.14                              | 0.08                              | -0.07 |       |
| 150-175                    | $4.98 \times 10^{-2}$                          | 0.37                          | 0.91                         | 1.08                         | 0.18                           | 0.56                           | 0.01                           | -0.02                          | -0.05                          | -0.01                          | 0.05                           | -0.03                          | 0.00                           | 0.00                              | 0.01                              | 0.00                              | 0.00                              | 0.00                              | 0.00                              | -0.02                             | -0.02                             | -0.01                             | 0.03                              | 0.00                              | 0.00                              | 0.15                              | -0.10                             | -0.47                             | 0.06                              | 0.15                              | 0.04                              | -0.12                             | -0.00                             | 0.09                              | 0.35                              | 0.04                              | 0.10                              | 0.16                              | 0.10                              | -0.09 |       |
| 175-200                    | $2.54 \times 10^{-2}$                          | 0.81                          | 1.18                         | 1.43                         | 0.25                           | 0.74                           | -0.00                          | -0.06                          | -0.07                          | -0.01                          | 0.06                           | -0.05                          | -0.01                          | 0.00                              | 0.01                              | 0.00                              | 0.00                              | 0.01                              | 0.00                              | -0.02                             | -0.03                             | -0.01                             | 0.04                              | 0.01                              | 0.00                              | 0.23                              | -0.11                             | -0.58                             | 0.02                              | 0.14                              | 0.07                              | -0.12                             | -0.00                             | 0.13                              | 0.47                              | 0.03                              | 0.12                              | 0.17                              | 0.10                              | -0.12 |       |
| 200-230                    | $1.37 \times 10^{-2}$                          | 1.02                          | 1.42                         | 1.75                         | 0.32                           | 0.89                           | 0.02                           | -0.09                          | -0.06                          | -0.01                          | 0.08                           | -0.05                          | -0.00                          | 0.00                              | 0.00                              | 0.00                              | 0.00                              | 0.00                              | -0.02                             | -0.04                             | -0.00                             | 0.04                              | 0.02                              | -0.00                             | 0.29                              | -0.12                             | -0.67                             | -0.01                             | 0.17                              | 0.05                              | -0.16                             | 0.02                              | 0.16                              | 0.58                              | 0.05                              | 0.16                              | 0.21                              | 0.16                              | -0.15                             |       |       |
| 230-260                    | $7.89 \times 10^{-3}$                          | 1.36                          | 1.59                         | 2.09                         | 0.43                           | 0.99                           | -0.01                          | -0.12                          | -0.08                          | 0.00                           | 0.07                           | -0.06                          | -0.01                          | 0.00                              | 0.01                              | 0.00                              | 0.00                              | 0.01                              | -0.00                             | -0.02                             | -0.04                             | 0.00                              | 0.05                              | 0.03                              | -0.01                             | 0.28                              | -0.11                             | -0.74                             | 0.04                              | 0.19                              | 0.09                              | -0.14                             | -0.00                             | 0.23                              | 0.65                              | 0.06                              | 0.23                              | 0.10                              | 0.22                              | -0.18 |       |
| 260-300                    | $4.43 \times 10^{-3}$                          | 1.58                          | 1.67                         | 2.30                         | 0.46                           | 1.06                           | 0.02                           | -0.11                          | -0.05                          | 0.01                           | 0.12                           | -0.06                          | -0.00                          | 0.01                              | 0.00                              | -0.00                             | -0.00                             | -0.00                             | -0.04                             | -0.06                             | 0.01                              | 0.07                              | 0.04                              | 0.00                              | 0.35                              | -0.19                             | -0.73                             | 0.00                              | 0.17                              | 0.05                              | -0.15                             | 0.04                              | 0.17                              | 0.68                              | 0.08                              | 0.22                              | 0.18                              | 0.22                              | -0.19                             |       |       |
| 300-380                    | $1.87 \times 10^{-3}$                          | 1.73                          | 1.80                         | 2.50                         | 0.56                           | 1.12                           | -0.02                          | -0.11                          | -0.09                          | 0.01                           | 0.09                           | -0.07                          | -0.01                          | 0.00                              | 0.01                              | -0.01                             | 0.00                              | 0.01                              | -0.00                             | -0.03                             | -0.06                             | -0.00                             | 0.06                              | 0.01                              | -0.01                             | 0.29                              | -0.18                             | -0.79                             | 0.03                              | 0.15                              | 0.08                              | -0.13                             | -0.00                             | 0.20                              | 0.76                              | 0.06                              | 0.30                              | 0.03                              | 0.29                              | -0.20 |       |
| 380-500                    | $6.20 \times 10^{-4}$                          | 2.42                          | 1.71                         | 2.96                         | 0.63                           | 1.03                           | 0.00                           | -0.08                          | -0.10                          | 0.04                           | 0.14                           | -0.07                          | -0.00                          | 0.01                              | 0.01                              | -0.00                             | -0.00                             | -0.00                             | -0.06                             | -0.08                             | 0.01                              | 0.08                              | 0.01                              | 0.02                              | 0.30                              | -0.26                             | -0.69                             | 0.09                              | 0.20                              | 0.05                              | -0.13                             | 0.05                              | 0.16                              | 0.59                              | 0.06                              | 0.36                              | 0.03                              | 0.39                              | -0.25                             |       |       |
| 500-700                    | $1.53 \times 10^{-4}$                          | 3.65                          | 1.68                         | 4.02                         | 0.57                           | 0.87                           | -0.08                          | -0.06                          | -0.14                          | 0.04                           | 0.15                           | 0.01                           | 0.02                           | 0.01                              | -0.00                             | 0.01                              | 0.03                              | 0.00                              | -0.05                             | -0.05                             | 0.03                              | 0.17                              | 0.04                              | 0.12                              | 0.02                              | -0.21                             | -0.56                             | 0.10                              | 0.03                              | 0.01                              | 0.06                              | -0.15                             | 0.06                              | 0.38                              | 0.13                              | 0.96                              | -0.09                             | 0.35                              | -0.18                             |       |       |
| 700-1000                   | $2.66 \times 10^{-5}$                          | 6.98                          | 1.85                         | 7.22                         | 1.02                           | 0.73                           | -0.09                          | 0.04                           | -0.13                          | 0.07                           | 0.17                           | 0.03                           | 0.03                           | 0.00                              | -0.01                             | -0.01                             | 0.02                              | 0.01                              | -0.07                             | -0.07                             | 0.05                              | 0.17                              | -0.01                             | 0.14                              | -0.15                             | -0.26                             | -0.44                             | 0.23                              | 0.08                              | 0.06                              | 0.13                              | -0.09                             | 0.02                              | 0.17                              | 0.19                              | 1.00                              | -0.17                             | 0.50                              | -0.17                             |       |       |
| 1000-1500                  | $2.66 \times 10^{-6}$                          | 17.05                         | 2.95                         | 17.31                        | 2.26                           | 0.71                           | 0.04                           | 0.16                           | -0.01                          | 0.06                           | 0.33                           | 0.10                           | 0.08                           | 0.05                              | -0.04                             | -0.00                             | -0.00                             | -0.01                             | -0.15                             | -0.14                             | 0.02                              | 0.22                              | -0.08                             | 0.16                              | -0.10                             | -0.49                             | -0.32                             | 0.21                              | 0.23                              | 0.08                              | -0.17                             | 0.01                              | -0.34                             | 0.28                              | 0.32                              | 1.21                              | -0.03                             | 0.69                              | -0.35                             |       |       |

**Table 2.** The combined Born-level single-differential cross section  $\frac{d\sigma}{dm_{\tilde{t}_2}}$ . The measurements are listed together with the statistical ( $\delta^{\text{stat}}$ ), systematic ( $\delta^{\text{sys}}$ ) and total ( $\delta^{\text{tot}}$ ) uncertainties. In addition the contributions from the individual correlated ( $\delta_{\text{cor}}^1$ - $\delta_{\text{cor}}^{35}$ ) and uncorrelated ( $\delta^{\text{unc}}$ ) systematic error sources are also provided. The luminosity uncertainty of 1.9% is not shown and not included in the overall systematic and total uncertainties.

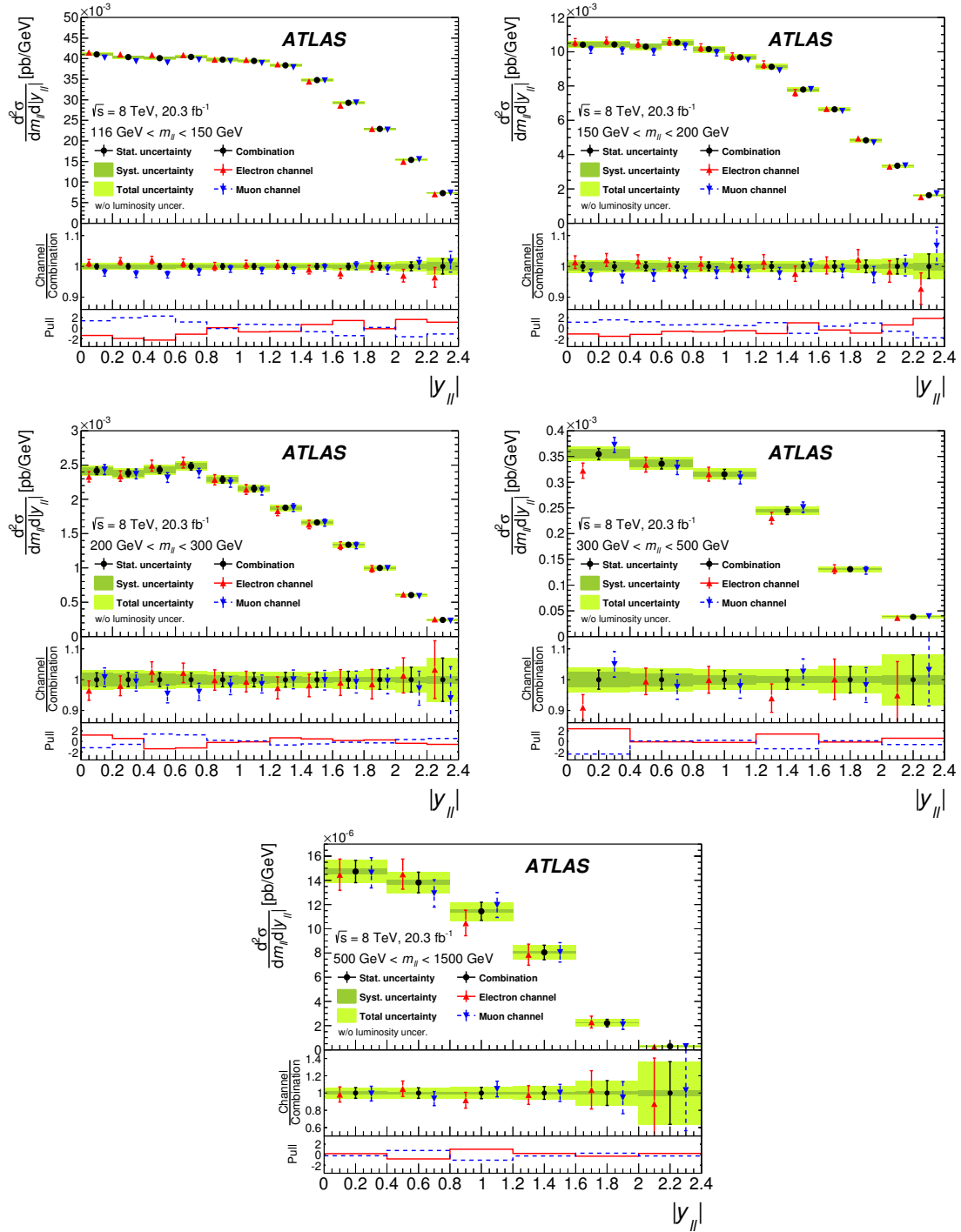




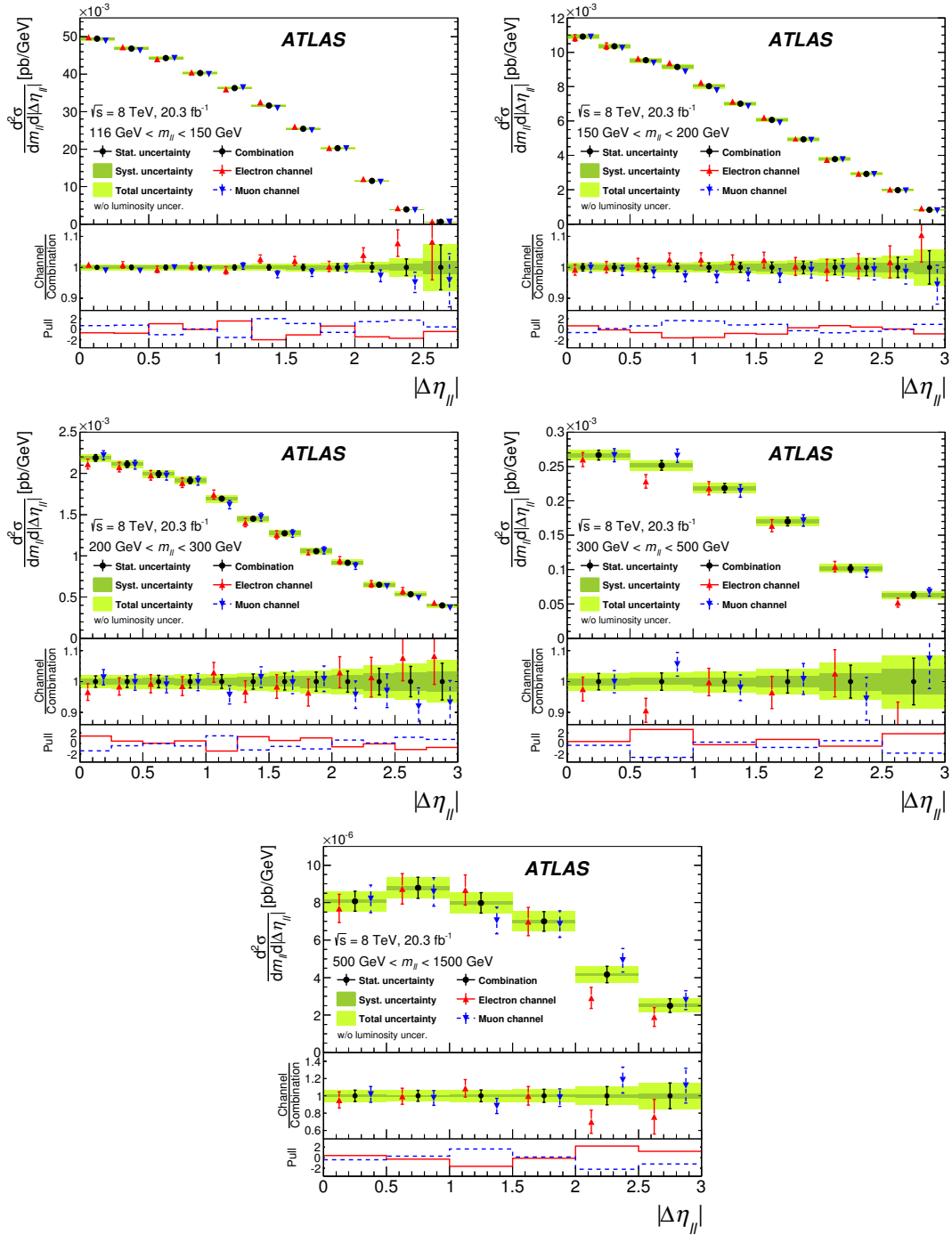


**Figure 6.** Comparison of the electron (red points), muon (blue points) and combined (black points) single-differential fiducial Born-level cross sections as a function of invariant mass  $m_{\ell\ell}$ . The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty on the combined cross sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The central panel shows the ratio of each measurement channel to the combined data, and the lower panel shows the pull of the electron (red) and muon (blue) channel measurements with respect to the combined data.





**Figure 7.** Comparison of the electron (red points), muon (blue points) and combined (black points) fiducial Born-level cross sections, differential in invariant mass  $m_{\ell\ell}$  and absolute dilepton rapidity  $|y_{\ell\ell}|$ . The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty on the combined cross sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The central panel shows the ratio of each measurement channel to the combined data, and the lower panel shows the pull of the electron (red) and muon (blue) channel measurements with respect to the combined data.



**Figure 8.** Comparison of the electron (red points), muon (blue points) and combined (black points) fiducial Born-level cross sections, differential in invariant mass  $m_{\ell\ell}$  and absolute dilepton pseudorapidity separation  $|\Delta\eta_{\ell\ell}|$ . The error bars represent the statistical uncertainty. The inner shaded band represents the systematic uncertainty on the combined cross sections, and the outer shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The central panel shows the ratio of each measurement channel to the combined data, and the lower panel shows the pull of the electron (red) and muon (blue) channel measurements with respect to the combined data.

## 9 Comparison to theoretical predictions

The combined fiducial cross sections at Born-level are compared to NNLO pQCD calculations using various PDFs. The calculations use the FEWZ 3.1 framework (see section 3), and include NLO EW corrections in the  $G_\mu$  [82] electroweak scheme. The dynamic scale  $m_{\ell\ell}$  is used in the calculation, and the renormalisation and factorisation scales are set to  $\mu_R = \mu_F = m_{\ell\ell}$ . The calculation includes the contribution of the non-resonant PI process,  $\gamma\gamma \rightarrow \ell\ell$ . This contribution is estimated at leading order (LO) using the photon PDF from the NNPDF2.3qed PDF set [22].

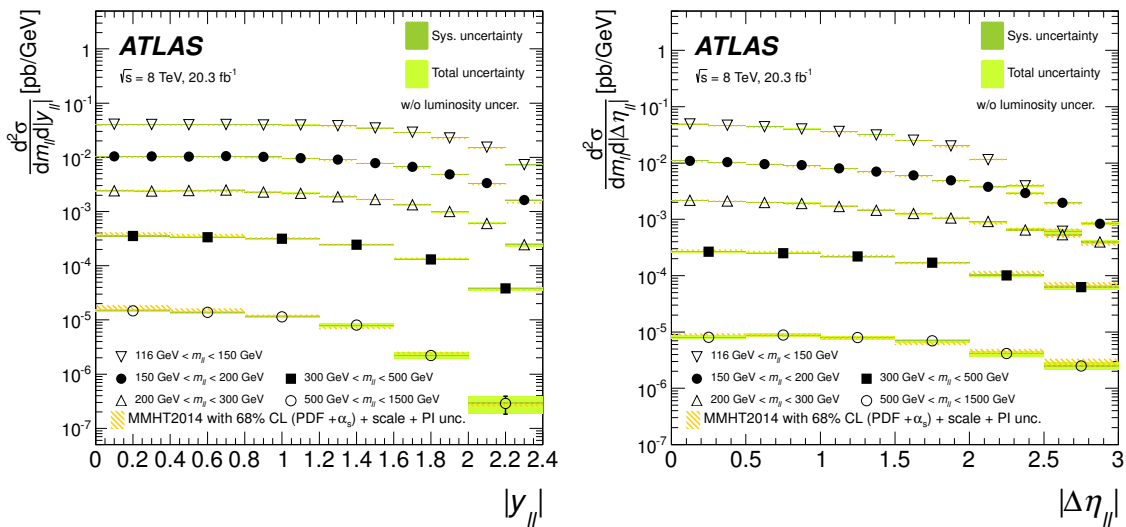
Theoretical predictions using the MMHT14 NNLO PDF set [20] are compared to the combined double-differential fiducial cross sections at Born-level as a function of  $m_{\ell\ell}$  and either  $|y_{\ell\ell}|$  or  $|\Delta\eta_{\ell\ell}|$  in figure 9. The single-differential cross section as a function of  $m_{\ell\ell}$  is shown in figure 10. The uncertainty bands assigned to the calculations show the combined 68% confidence level (CL) PDF and  $\alpha_S$  variation, the renormalisation and factorisation scale uncertainties and the PI uncertainty. The  $\alpha_S$  uncertainty is determined by varying  $\alpha_S$  by 0.001 with respect to its default value of 0.118. The scale uncertainties are defined by the envelope of variations in which the scales are changed by factors of two subject to the constraint  $0.5 \leq \mu_R/\mu_F \leq 2$ . The relative uncertainty on the PI contribution represents the region covering 68% of the NNPDF2.3qed MC replicas,<sup>2</sup> corresponding to rather large values of 62%–92% depending on the bin.

Figures 11 and 12 show the ratio of theoretical predictions for the double-differential cross sections to the combined measurements. The corresponding ratios for the single-differential cross section are shown in the middle and lower panels of figure 10. The PI contribution reaches up to 15% in certain regions of phase space, as can be seen in the middle panels of figure 10 and the left panels of figures 11 and 12 where a comparison is shown between the ratios for the default calculation and a calculation neglecting the PI contribution. In the regions where the PI contribution is large the PI uncertainty dominates the total uncertainty band, otherwise the PDF uncertainty is dominant. Thus it can be inferred from, e.g., the middle panel of figure 10, that the PDF (PI) uncertainty dominates the uncertainty band at small (large)  $m_{\ell\ell}$ . The uncertainties are similar at about  $m_{\ell\ell} \simeq 200$  GeV.

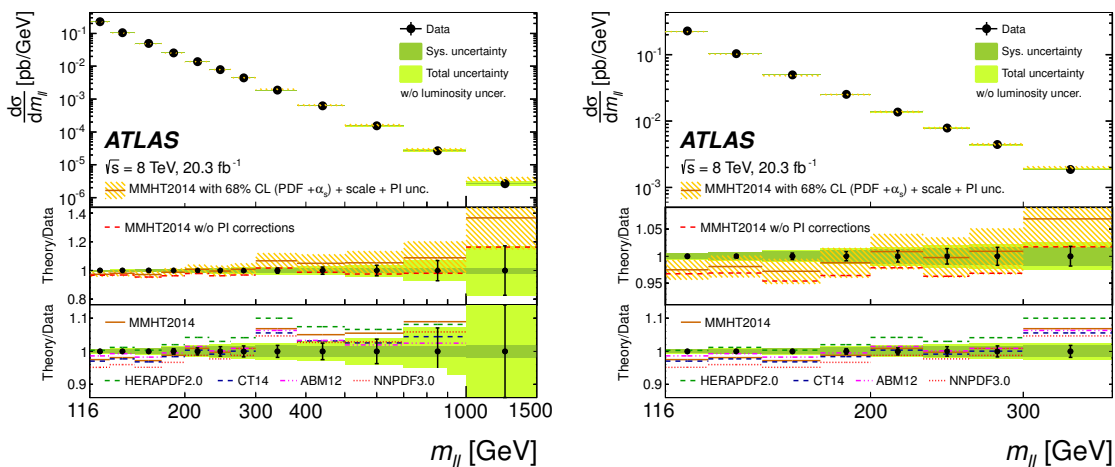
The uncertainties on the theoretical calculation are in general larger than those on the measurement for most of the phase space, indicating that the data presented here have the potential to constrain the theoretical predictions. The calculation including the PI contribution is in general in agreement with the data. However, it seems to undershoot the data at small  $m_{\ell\ell}$  as can be seen in all three figures.

The change in the theoretical prediction when replacing the MMHT PDF by other NNLO PDFs such as HERAPDF2.0 [83], CT14 [18], ABM12 [84] or NNPDF3.0 [19] is shown in the lower panels of figure 10 and the right panels of figures 11 and 12. For ease of visibility, no separate uncertainty bands are shown for each individual PDF. However, they have been calculated and found to be smaller (ABM12), larger (CT14, NNPDF3.0) or

<sup>2</sup>The NNPDF Collaboration provides a large number of MC replicas in order to represent the PDF, where the central PDF is given by the mean of all replicas and the uncertainty is defined as the region covering 68% of all MC replicas.



**Figure 9.** The combined double-differential cross sections as a function of invariant mass  $m_{\ell\ell}$  and absolute dilepton rapidity  $|y_{\ell\ell}|$  (left panel) and as a function of  $m_{\ell\ell}$  and absolute dilepton pseudorapidity separation  $|\Delta\eta_{\ell\ell}|$  (right panel) at the Born-level within the fiducial region with statistical, systematic and total uncertainties, excluding the 1.9% uncertainty on the luminosity. Data are compared to combined NNLO pQCD and NLO EW calculations using the MMHT2014 PDF, where the uncertainty band displays the combined 68% confidence level (CL) PDF and  $\alpha_s$  variation, the renormalisation and factorisation scale uncertainties and the PI uncertainty.



**Figure 10.** The combined single-differential cross section as a function of invariant mass  $m_{\ell\ell}$  at the Born-level within the fiducial region with statistical, systematic and total uncertainties, excluding the 1.9% uncertainty on the luminosity. Data are compared to combined NNLO pQCD and NLO EW calculations using the MMHT2014 PDF, where the uncertainty band displays the combined 68% confidence level (CL) PDF and  $\alpha_s$  variation, the renormalisation and factorisation scale uncertainties and the PI uncertainty. The two ratio panels show the ratio of the calculation, both with and without the PI contribution with respect to data (middle panel), as well as the ratio for calculations using different PDFs (bottom panel). On the right, the results are shown for a restricted range of  $m_{\ell\ell}$ .

|            | $m_{\ell\ell}$ | $ y_{\ell\ell} $ | $ \Delta\eta_{\ell\ell} $ |
|------------|----------------|------------------|---------------------------|
| MMHT2014   | 18.2/12        | 59.3/48          | 62.8/47                   |
| CT14       | 16.0/12        | 51.0/48          | 61.3/47                   |
| NNPDF3.0   | 20.0/12        | 57.6/48          | 62.1/47                   |
| HERAPDF2.0 | 15.1/12        | 55.5/48          | 60.8/47                   |
| ABM12      | 14.1/12        | 57.9/48          | 53.5/47                   |

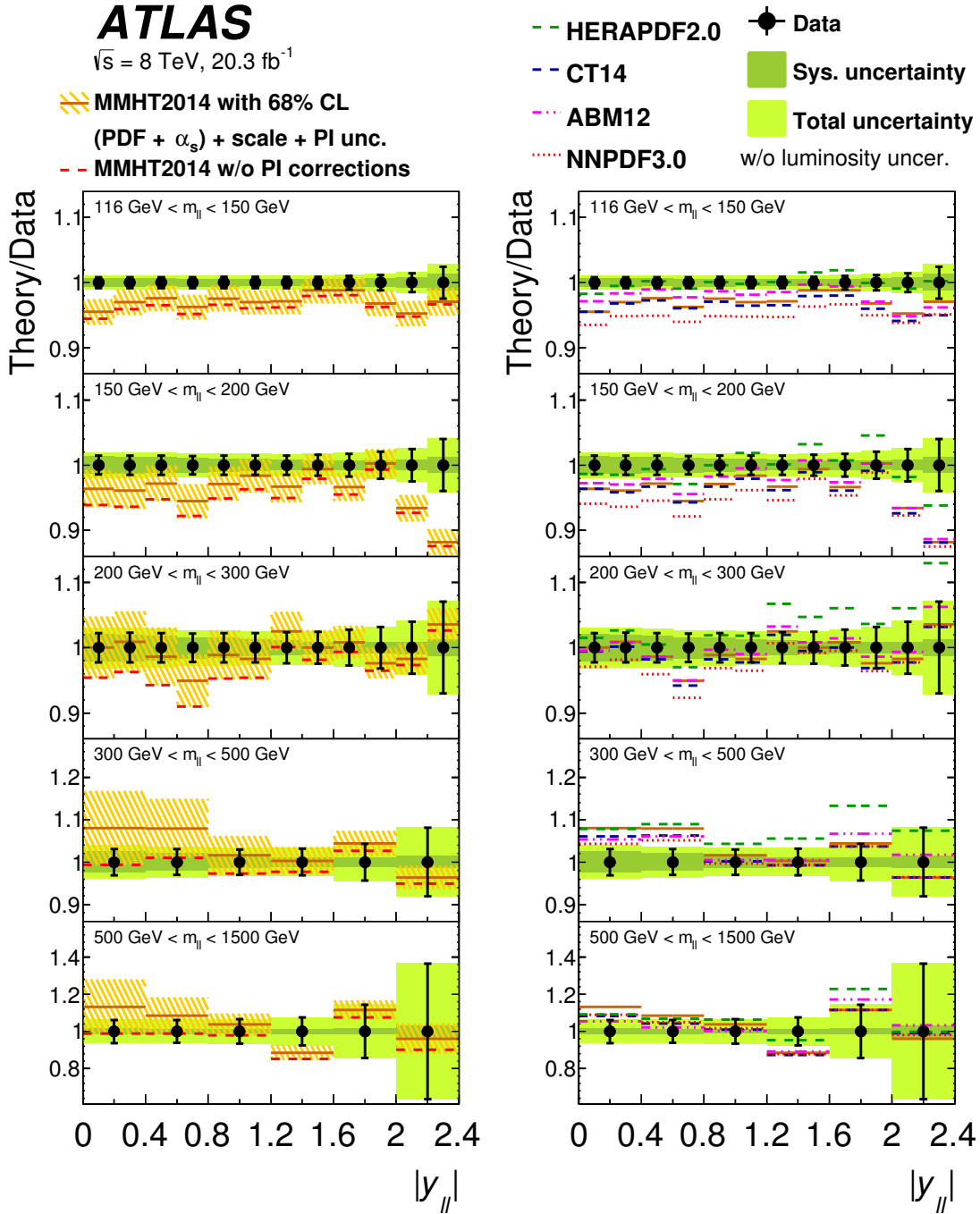
**Table 5.** The  $\chi^2/dof$  values for the compatibility of data and theory after the minimisation procedure.

even much larger (HERAPDF2.0) than the ones from MMHT14 when scaled to the 68% CL. The calculations using the various PDFs generally agree with the data, with the one using NNPDF3.0 showing the least agreement at low  $m_{\ell\ell}$ . In particular at low  $m_{\ell\ell}$ , the differences between the predictions in all three figures are larger than the total uncertainty of the measurement, indicating the sensitivity of the data to the PDFs, and the potential to constrain them.

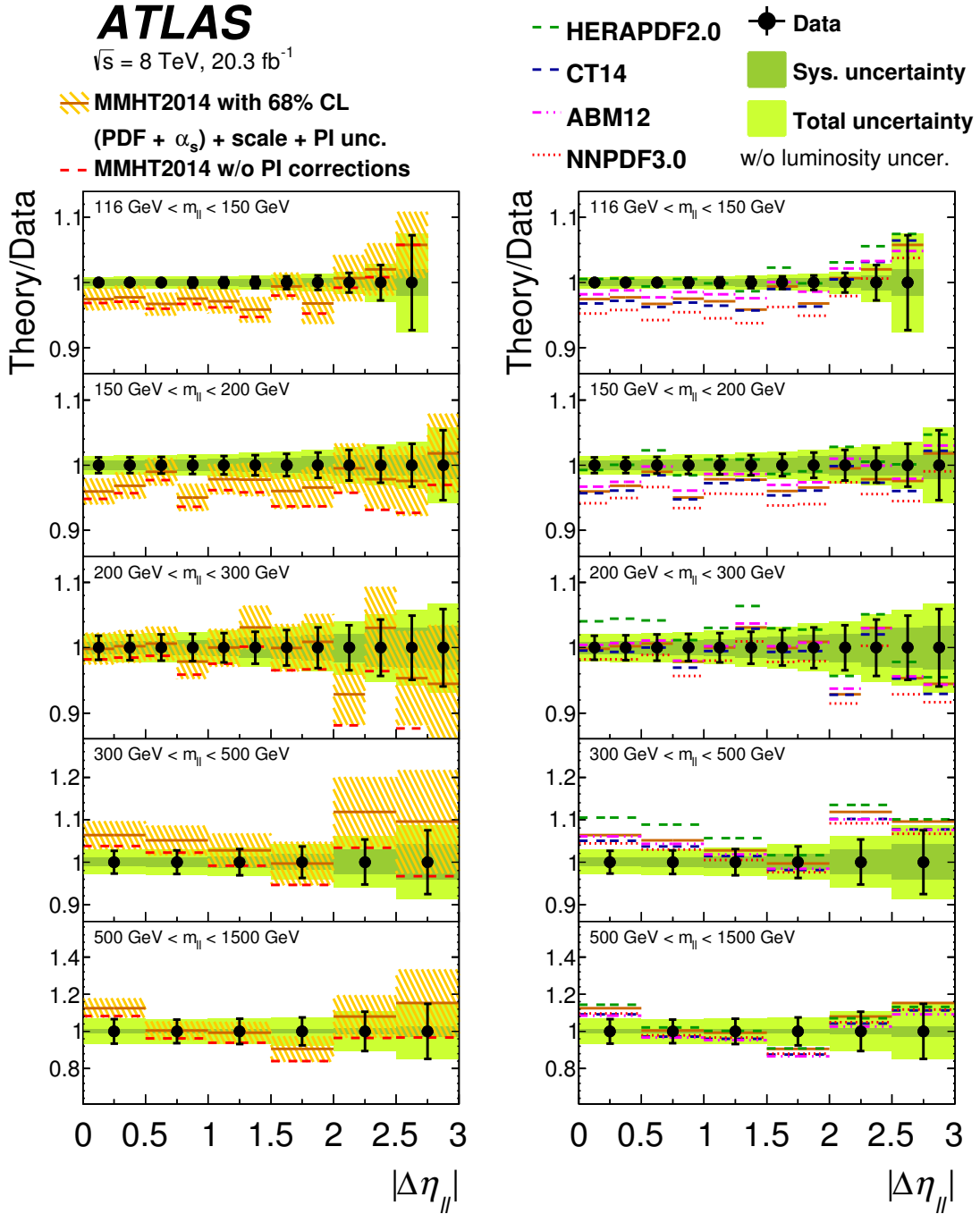
In order to quantitatively assess the compatibility between data and theory, a  $\chi^2$  minimisation procedure as implemented in the xFitter package [85] is used. All correlated and uncorrelated experimental uncertainties (see tables 2, 3 and 4), the luminosity uncertainty and the theoretical uncertainties are included in the  $\chi^2$  function. The correlated theoretical uncertainties include the uncertainties on the respective PDF, the PI contribution,  $\alpha_S$ , and the scale. The PDF uncertainties for all the PDF sets except for the photon PDF are further decomposed into the full set of eigenvectors, where in the case of NNPDF3.0 the replica representation is transformed into an eigenvector representation. Uncorrelated theoretical uncertainties arising from the statistical precision of the calculations are also taken into account but are at the level of 0.1% for the calculation of the DY and 0.2% for the PI cross sections. All correlated uncertainties are included as nuisance parameters. After minimisation, the central values of the nuisance parameters may be shifted from unity and their uncertainties may be reduced. A sizeable shift and reduction in uncertainty indicates that the data can constrain the respective nuisance parameter.

The  $\chi^2$  minimisation is performed separately for all five PDF sets and for all three distributions shown in figures 10, 11 and 12. The  $\chi^2$  values after minimisation are given in table 5. They indicate general compatibility between the data and the theory, mainly due to the fact that the theoretical uncertainties for all PDF sets except for ABM12 are larger than the ones for MMHT14 shown in the figures. The overall best agreement with the data is found for the calculations using ABM12, especially when taking into account their smaller PDF uncertainties.

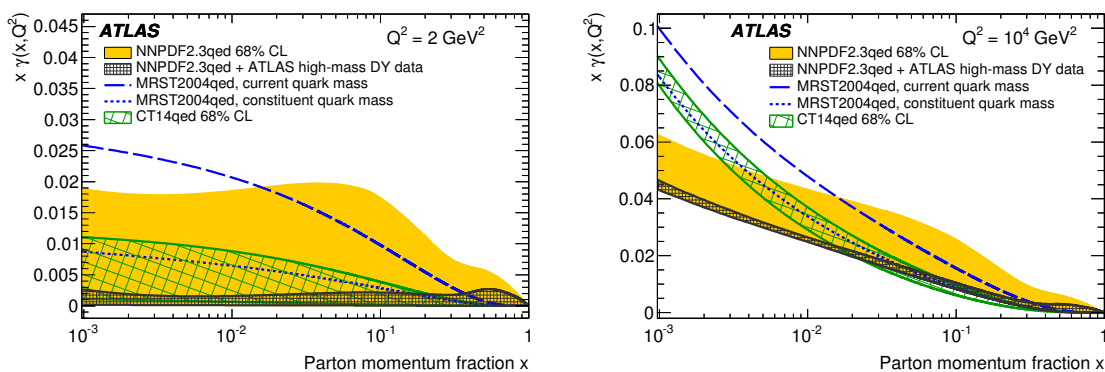
The impact of this data on existing PDF sets can be inferred using Bayesian reweighting [86], which has been further developed and validated by the NNPDF collaboration in the context of their MC replicas [87, 88]. Each replica is used together with this data set in the  $\chi^2$  minimisation described above, and a weight is assigned based on the resulting



**Figure 11.** The ratio of theoretical NNLO pQCD and NLO EW calculations to the combined double-differential cross section as a function of invariant mass  $m_{\ell\ell}$  and absolute dilepton rapidity  $|y_{\ell\ell}|$  at the Born-level within the fiducial region with statistical, systematic and total uncertainties, excluding the 1.9% uncertainty on the luminosity. The calculations are shown for the MMHT14 PDF with and without the PI contribution on the left side and for MMHT14, HERAPDF2.0, CT10, ABM12 and NNPDF3.0 on the right side. The uncertainty band on the left side displays the combined 68% confidence level (CL) PDF and  $\alpha_s$  variation, the renormalisation and factorisation scale uncertainties and the PI uncertainty.



**Figure 12.** The ratio of theoretical NNLO pQCD and NLO EW calculations to the combined double-differential cross section as a function of invariant mass  $m_{\ell\ell}$  and absolute dilepton pseudo-rapidity separation  $|\Delta\eta_{\ell\ell}|$  at Born-level within the fiducial region with statistical, systematic and total uncertainties, excluding the 1.9% uncertainty on the luminosity. The calculations are shown for the MMHT14 PDF with and without the PI contribution on the left side and for MMHT14, HERAPDF2.0, CT10, ABM12 and NNPDF3.0 on the right side. The uncertainty band on the left side displays the combined 68% confidence level (CL) PDF and  $\alpha_s$  variation, the renormalisation and factorisation scale uncertainties and the PI uncertainty.



**Figure 13.** The 68% confidence level interval of the NNPDF2.3qed NNLO photon PDF as a function of momentum fraction  $x$  at the input scale  $Q_0^2 = 2 \text{ GeV}^2$  (left panel) and  $Q^2 = 10^4 \text{ GeV}^2$  (right panel) before (yellow solid area) [22] and after (grey shaded area) inclusion of the double-differential cross section measurement as a function of invariant mass  $m_{\ell\ell}$  and absolute dilepton rapidity  $|y_{\ell\ell}|$ . Also shown is the MRST2004qed photon PDF in a current quark (blue dashed line) and a constituent quark (blue dotted line) mass scheme [21], and the 68% CL band (green shaded area) for the CT14qed photon PDF [89].

$\chi^2$ . Replicas not describing the data well get a smaller weight assigned, and a new PDF is derived by including the weights in the calculation of the central value and the PDF uncertainty, i.e., without performing a new global PDF fit.

Bayesian reweighting is used for the 100 MC replicas representing the NNPDF2.3qed photon PDF obtained in NNLO fits. The results of the reweighting are shown in figure 13. The solid yellow area represents the 68% confidence level interval of the NNPDF2.3qed photon PDF at  $Q^2 = 2 \text{ GeV}^2$  and at  $Q^2 = 10^4 \text{ GeV}^2$ , which are also displayed in ref. [22]. In addition, the MRST2004qed photon PDF [21] using two different quark mass schemes (see section 7) and the recent CT14qed photon PDF [89] are displayed, which exhibit a different PDF evolution compared to NNPDF2.3qed as can be seen when comparing the two plots at the input scale and at  $Q^2 = 10^4 \text{ GeV}^2$ . The shaded area indicates the new PDF after inclusion of this data by means of Bayesian reweighting, where the  $\chi^2$  minimisations are performed for the double-differential cross section as a function of  $m_{\ell\ell}$  and  $|y_{\ell\ell}|$  using the prediction based on the MMHT14 PDF. The reduction of uncertainties is rather large and confirms the strong sensitivity of this data to the photon PDF. Using the double-differential cross section as a function of  $m_{\ell\ell}$  and  $|\Delta\eta_{\ell\ell}|$  instead, a slightly smaller impact is found. This can be explained by the fact that the contributions from the PI process are largest in the regions of small  $|y_{\ell\ell}|$  and large  $|\Delta\eta_{\ell\ell}|$ , where the uncertainties of the measurement are smallest for  $|y_{\ell\ell}|$  but largest for  $|\Delta\eta_{\ell\ell}|$ .

Inspection of the optimised experimental nuisance parameters of those minimisations with the best  $\chi^2$  values shows that the largest pulls and uncertainty reductions are found for the luminosity. Larger values for the data luminosity by about 1.1 and 1.2 standard deviations are favoured for the minimisations in  $|y_{\ell\ell}|$  and  $|\Delta\eta_{\ell\ell}|$  respectively, leading to smaller values for the experimental cross section. For the MMHT14 PDF, the largest pulls and reduction of uncertainty by about 25% is found for an eigenvector (“eigenvector 21”)



particularly sensitive to the sea and strange sea quark distribution, where previous ATLAS data on on-shell  $W$  and  $Z$  production [6] is already the most constraining data set in one eigenvector direction [20].

## 10 Conclusion

The double-differential fiducial cross sections  $d^2\sigma/dm_{\ell\ell}d|y_{\ell\ell}|$  and  $d^2\sigma/dm_{\ell\ell}d|\Delta\eta_{\ell\ell}|$  for the Drell-Yan and photon induced production of dileptons in the invariant mass range  $116 < m_{\ell\ell} < 1500$  GeV are measured, as well as the single-differential fiducial cross section  $d\sigma/dm_{\ell\ell}$ . The measurements are performed in the electron and muon channels using  $20.3\text{fb}^{-1}$  of integrated luminosity collected by the ATLAS detector at the LHC in  $pp$  collisions at  $\sqrt{s} = 8\text{TeV}$ . The two measurements are combined taking into account the systematic uncertainty correlations. The combined cross sections achieve an experimental precision of better than 1% at low  $m_{\ell\ell}$ , excluding the overall uncertainty in the luminosity measurement of 1.9%.

The fiducial cross sections are compared to fixed order theoretical predictions at NNLO accuracy using a selection of recent PDF sets. The calculations are performed using renormalisation and factorisation scales equal to  $m_{\ell\ell}$ , and are corrected for additional higher-order electroweak radiative effects. Theoretical uncertainties arising from the PDFs, the choice of scale and a variation of  $\alpha_S$  are calculated and are found to be larger than the measurement uncertainties, indicating the data has the potential to constrain PDFs. This is confirmed by a  $\chi^2$  minimisation procedure comparing data to theoretical predictions, which in combination with a Bayesian reweighting method shows a dramatic reduction of the uncertainties on the photon PDF.

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## A Tables: separate cross sections in the electron and muon channels

| $m_{ee}$<br>[GeV] | $\frac{d\sigma}{dm_{ee}}$<br>[pb/GeV] | $\delta^{\text{stat}}$<br>[%] | $\delta^{\text{sys}}$<br>[%] | $\delta^{\text{tot}}$<br>[%] | $\delta^{\text{trig}}_{\text{cor}}$<br>[%] | $\delta^{\text{trig}}_{\text{unc}}$<br>[%] | $\delta^{\text{reco}}_{\text{cor}}$<br>[%] | $\delta^{\text{id}}_{\text{cor}}$<br>[%] | $\delta^{\text{iso}}_{\text{cor}}$<br>[%] | $\delta^{\text{iso}}_{\text{unc}}$<br>[%] | $\delta^{\text{Eres}}_{\text{cor}}$<br>[%] | $\delta^{\text{Escale}}_{\text{cor}}$<br>[%] | $\delta^{\text{mult.}}_{\text{cor}}$<br>[%] | $\delta^{\text{mult.}}_{\text{unc}}$<br>[%] | $\delta^{\text{top}}_{\text{cor}}$<br>[%] | $\delta^{\text{diboson}}_{\text{cor}}$<br>[%] | $\delta^{\text{bgMC}}_{\text{unc}}$<br>[%] | $\delta^{\text{MC}}_{\text{unc}}$<br>[%] | $k_{\text{dressed}}$ |
|-------------------|---------------------------------------|-------------------------------|------------------------------|------------------------------|--|--|--|--|---|---|--|--|---|---|---|---|--|--|----------------------|
| 116–130           | $2.31 \times 10^{-1}$                 | 0.5                           | 0.8                          | 1.0                          | -0.1                                       | 0.0  | 0.0  | -0.3                                     | 0.0                                       | 0.0                                       | 0.1  | 0.5  | -0.5  | 0.1   | -0.3                                      | -0.1  | 0.0  | 0.1                                      | 1.047                |
| 130–150           | $1.05 \times 10^{-1}$                 | 0.7                           | 1.0                          | 1.2                          | -0.1                                       | 0.0  | -0.1                                       | -0.4                                     | 0.0                                       | 0.1                                       | 0.1  | 0.4  | -0.7  | 0.2   | -0.5                                      | -0.2  | 0.1  | 0.1                                      | 1.046                |
| 150–175           | $5.06 \times 10^{-2}$                 | 0.8                           | 1.3                          | 1.6                          | 0.0  | 0.1  | -0.1                                       | -0.5                                     | 0.0                                       | 0.1                                       | 0.1  | 0.4  | -0.8  | 0.3   | -0.7                                      | -0.2  | 0.1  | 0.1                                      | 1.047                |
| 175–200           | $2.60 \times 10^{-2}$                 | 1.2                           | 1.6                          | 2.0                          | -0.1                                       | 0.1  | -0.1                                       | -0.6                                     | 0.0                                       | 0.1                                       | 0.0  | 0.5  | -0.9  | 0.3   | -0.9                                      | -0.3  | 0.2  | 0.1                                      | 1.052                |
| 200–230           | $1.39 \times 10^{-2}$                 | 1.5                           | 2.0                          | 2.5                          | -0.1                                       | 0.1  | -0.1                                       | -0.7                                     | 0.0                                       | 0.2                                       | 0.1  | 0.7  | -1.2  | 0.4   | -1.1                                      | -0.4  | 0.2  | 0.2                                      | 1.053                |
| 230–260           | $7.95 \times 10^{-3}$                 | 2.0                           | 2.2                          | 3.0                          | -0.1                                       | 0.1  | -0.2                                       | -0.7                                     | -0.1                                      | 0.2                                       | 0.1  | 1.0  | -1.1  | 0.4   | -1.3                                      | -0.4  | 0.3  | 0.2                                      | 1.056                |
| 260–300           | $4.43 \times 10^{-3}$                 | 2.4                           | 2.3                          | 3.3                          | -0.1                                       | 0.1  | -0.2                                       | -0.7                                     | -0.1                                      | 0.2                                       | 0.1  | 0.9  | -1.3  | 0.5   | -1.3                                      | -0.6  | 0.4  | 0.2                                      | 1.058                |
| 300–380           | $1.84 \times 10^{-3}$                 | 2.6                           | 2.5                          | 3.6                          | -0.1                                       | 0.2  | -0.2                                       | -0.8                                     | -0.1                                      | 0.3                                       | 0.1  | 1.3  | -1.1  | 0.4   | -1.4                                      | -0.6  | 0.4  | 0.2                                      | 1.063                |
| 380–500           | $5.99 \times 10^{-4}$                 | 3.6                           | 2.7                          | 4.5                          | -0.1                                       | 0.2  | -0.2                                       | -0.8                                     | -0.2                                      | 0.5                                       | 0.1  | 1.6  | -1.4  | 0.5   | -1.1                                      | -0.6  | 0.5  | 0.2                                      | 1.067                |
| 500–700           | $1.52 \times 10^{-4}$                 | 5.3                           | 2.6                          | 6.0                          | -0.1                                       | 0.2  | -0.2                                       | -0.8                                     | -0.2                                      | 0.7                                       | 0.1  | 2.0  | -0.7  | 0.5   | -0.7                                      | -0.6  | 0.5  | 0.3                                      | 1.075                |
| 700–1000          | $2.64 \times 10^{-5}$                 | 10.2                          | 3.3                          | 10.7                         | -0.2                                       | 0.4  | -0.2                                       | -0.8                                     | -0.3                                      | 1.4                                       | 0.1  | 2.3  | -0.6  | 0.8   | -0.4                                      | -0.6  | 0.7  | 0.4                                      | 1.085                |
| 1000–1500         | $3.23 \times 10^{-6}$                 | 22.5                          | 5.8                          | 23.2                         | -0.7                                       | 0.9  | -0.2                                       | -0.8                                     | -0.3                                      | 3.5                                       | 0.0  | 2.8  | -1.9  | 1.6   | -0.3                                      | -0.6  | 2.1  | 0.2                                      | 1.100                |

**Table 6.** The electron channel Born-level single-differential cross section  $\frac{d\sigma}{dm_{ee}}$ . The measurements are listed together with the statistical ( $\delta^{\text{stat}}$ ), systematic ( $\delta^{\text{sys}}$ ) and total ( $\delta^{\text{tot}}$ ) uncertainties. In addition the contributions from the individual correlated (cor) and uncorrelated (unc) systematic error sources are also provided consisting of the trigger efficiency ( $\delta^{\text{trig}}$ ), electron reconstruction efficiency ( $\delta^{\text{reco}}$ ), electron identification efficiency ( $\delta^{\text{id}}$ ), the isolation efficiency ( $\delta^{\text{iso}}$ ), the electron energy resolution ( $\delta^{\text{Eres}}$ ), the electron energy scale ( $\delta^{\text{Escale}}$ ), the multijet and  $W$ +jets background ( $\delta^{\text{mult.}}$ ), the top and diboson background normalisation ( $\delta^{\text{top}}$ ,  $\delta^{\text{diboson}}$ ), the top and diboson background MC statistical uncertainty ( $\delta^{\text{bgMC}}$ ), and the signal MC statistical uncertainty ( $\delta^{\text{MC}}$ ). The ratio of the dressed-level to Born-level predictions ( $k_{\text{dressed}}$ ) is also provided. The luminosity uncertainty of 1.9% is not shown and not included in the overall systematic and total uncertainties.





| $m_{\mu\mu}$<br>[GeV] | $\frac{d\sigma}{dm_{\mu\mu}}$<br>[pb/GeV] | $\delta^{\text{stat}}$<br>[%] | $\delta^{\text{sys}}$<br>[%] | $\delta^{\text{tot}}$<br>[%] | $\delta_{\text{cor}}^{\text{trig}}$<br>[%] | $\delta_{\text{cor}}^{\text{reco}}$<br>[%] | $\delta_{\text{cor}}^{\text{MSres}}$<br>[%] | $\delta_{\text{cor}}^{\text{IDres}}$<br>[%] | $\delta_{\text{cor}}^{\text{pT}}$<br>[%] | $\delta_{\text{cor}}^{\text{iso}}$<br>[%] | $\delta_{\text{cor}}^{\text{top}}$<br>[%] | $\delta_{\text{cor}}^{\text{diboson}}$<br>[%] | $\delta_{\text{unc}}^{\text{bgMC}}$<br>[%] | $\delta_{\text{cor}}^{\text{mult.}}$<br>[%] | $\delta_{\text{unc}}^{\text{mult.}}$<br>[%] | $\delta_{\text{unc}}^{\text{MC}}$<br>[%] | $k_{\text{dressed}}$ |
|-----------------------|---|-------------------------------|------------------------------|------------------------------|--|--|---|---|--|---|---|---|--|---|---|--|----------------------|
| 116 – 130             | $2.25 \times 10^{-1}$                     | 0.5                           | 0.6                          | 0.8                          | -0.1                                       | -0.4                                       | -0.1  | -0.1  | -0.4                                     | -0.1                                      | -0.3                                      | -0.1  | 0.0  | 0.0   | 0.1   | 0.1                                      | 1.055                |
| 130 – 150             | $1.04 \times 10^{-1}$                     | 0.6                           | 0.7                          | 0.9                          | -0.1                                       | -0.4                                       | -0.1  | 0.0   | -0.3                                     | -0.1                                      | -0.5                                      | -0.1  | 0.1  | 0.0   | 0.1   | 0.1                                      | 1.047                |
| 150 – 175             | $4.94 \times 10^{-2}$                     | 0.8                           | 0.9                          | 1.2                          | -0.1                                       | -0.4                                       | 0.0   | 0.0   | -0.2                                     | -0.1                                      | -0.7                                      | -0.2  | 0.1  | -0.1  | 0.1   | 0.1                                      | 1.043                |
| 175 – 200             | $2.51 \times 10^{-2}$                     | 1.1                           | 1.2                          | 1.6                          | -0.1                                       | -0.5                                       | 0.0   | 0.0   | -0.2                                     | -0.1                                      | -1.0                                      | -0.3  | 0.1  | -0.1  | 0.2   | 0.1                                      | 1.040                |
| 200 – 230             | $1.37 \times 10^{-2}$                     | 1.4                           | 1.5                          | 2.0                          | -0.1                                       | -0.5                                       | 0.0   | -0.1  | -0.2                                     | -0.1                                      | -1.2                                      | -0.4  | 0.2  | -0.1  | 0.3   | 0.2                                      | 1.037                |
| 230 – 260             | $7.87 \times 10^{-3}$                     | 1.8                           | 1.6                          | 2.5                          | -0.1                                       | -0.5                                       | 0.0   | 0.1   | -0.3                                     | -0.1                                      | -1.3                                      | -0.4  | 0.3  | -0.1  | 0.5   | 0.2                                      | 1.036                |
| 260 – 300             | $4.45 \times 10^{-3}$                     | 2.1                           | 1.7                          | 2.7                          | -0.1                                       | -0.6                                       | 0.0   | -0.1  | -0.2                                     | -0.2                                      | -1.4                                      | -0.5  | 0.3  | -0.1  | 0.5   | 0.2                                      | 1.037                |
| 300 – 380             | $1.90 \times 10^{-3}$                     | 2.3                           | 1.9                          | 3.0                          | -0.1                                       | -0.6                                       | 0.1   | 0.0   | -0.3                                     | -0.2                                      | -1.4                                      | -0.6  | 0.4  | -0.2  | 0.7   | 0.2                                      | 1.035                |
| 380 – 500             | $6.40 \times 10^{-4}$                     | 3.2                           | 1.8                          | 3.7                          | -0.1                                       | -0.7                                       | -0.1  | -0.1  | -0.2                                     | -0.3                                      | -1.2                                      | -0.5  | 0.5  | -0.1  | 0.8   | 0.2                                      | 1.037                |
| 500 – 700             | $1.54 \times 10^{-4}$                     | 5.0                           | 2.0                          | 5.4                          | -0.1                                       | -0.8                                       | -0.1  | 0.0   | -0.2                                     | -0.4                                      | -0.9                                      | -0.5  | 0.6  | -1.3  | 0.0   | 0.2                                      | 1.036                |
| 700 – 1000            | $2.66 \times 10^{-5}$                     | 9.6                           | 2.1                          | 9.8                          | -0.1                                       | -0.8                                       | -0.5  | -0.1  | -0.4                                     | -0.5                                      | -0.5                                      | -0.5  | 0.8  | -1.3  | 0.0   | 0.4                                      | 1.040                |
| 1000 – 1500           | $2.17 \times 10^{-6}$                     | 26.0                          | 2.7                          | 26.2                         | -0.1                                       | -1.1                                       | -0.1  | -1.0  | -0.3                                     | -0.6                                      | -0.4                                      | -0.6  | 1.5  | -1.4  | 0.0   | 0.4                                      | 1.043                |

**Table 9.** The muon channel Born-level single-differential cross section  $\frac{d\sigma}{dm_{\mu\mu}}$ . The measurements are listed together with the statistical ( $\delta^{\text{stat}}$ ), systematic ( $\delta^{\text{sys}}$ ) and total ( $\delta^{\text{tot}}$ ) uncertainties. In addition the contributions from the individual correlated (cor) and uncorrelated (unc) systematic error sources are also provided consisting of the trigger efficiency ( $\delta^{\text{trig}}$ ), muon reconstruction efficiency ( $\delta^{\text{reco}}$ ), the MS resolution ( $\delta^{\text{MSres}}$ ), the ID resolution ( $\delta^{\text{IDres}}$ ), the muon transverse momentum scale ( $\delta^{\text{pT}}$ ), the isolation efficiency ( $\delta^{\text{iso}}$ ), the top and diboson background normalisation ( $\delta^{\text{top}}$ ,  $\delta^{\text{diboson}}$ ), the top and diboson background MC statistical uncertainty ( $\delta^{\text{bgMC}}$ ), the multijet background ( $\delta^{\text{mult}}$ ) and the signal MC statistical uncertainty ( $\delta^{\text{MC}}$ ). The ratio of the dressed-level to Born-level predictions ( $k_{\text{dressed}}$ ) is also provided. The luminosity uncertainty of 1.9% is not shown and not included in the overall systematic and total uncertainties.





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 F. Dittus<sup>32</sup>, F. Djama<sup>87</sup>, T. Djobava<sup>53b</sup>, J.I. Djuvsland<sup>60a</sup>, M.A.B. do Vale<sup>26c</sup>, D. Dobos<sup>32</sup>,  
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