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Measurement of angular correlations in Drell–Yan lepton pairs to probe Z/γ^* boson transverse momentum at $\sqrt{s}=7$ TeV with the ATLAS detector ☆☆

ATLAS Collaboration ⋆

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ABSTRACT

A measurement of angular correlations in Drell–Yan lepton pairs via the ϕ^*_η observable is presented. This variable probes the same physics as the Z/γ^* boson transverse momentum with a better experimental resolution. The $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ decays produced in proton–proton collisions at a centre-of-mass energy of $\sqrt{s}=7$ TeV are used. The data were collected with the ATLAS detector at the LHC and correspond to an integrated luminosity of 4.6 fb^{-1}. Normalised differential cross sections as a function of ϕ^*_η are measured separately for electron and muon decay channels. These channels are then combined for improved accuracy. The cross section is also measured double differentially as a function of ϕ^*_η for three independent bins of the Z boson rapidity. The results are compared to QCD calculations and to predictions from different Monte Carlo event generators. The data are reasonably well described, in all measured Z boson rapidity regions, by resummed QCD predictions combined with fixed-order perturbative QCD calculations or by some Monte Carlo event generators. The measurement precision is typically better by one order of magnitude than present theoretical uncertainties.

1. Introduction

In hadron collisions at TeV energies the vector bosons W and Z/γ^* are copiously produced with non-zero momentum transverse to the beam direction (p_T) because of radiation of quarks and gluons from the initial-state partons. In this context the signatures $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ provide an ideal testing ground for QCD due to the absence of colour flow between the initial and final state [1–3]. The study of the low p^Z_T spectrum ($p^Z_\mathrm{T} < m_Z$), which dominates the cross section, has important implications on the understanding of Higgs boson production since the transverse-momentum resummation formalism required to describe the Z/γ^* boson cross section is valid also for the Higgs boson [4–7]. A precise understanding of the p^Z_T spectrum is also necessary to further improve the modelling of W boson production in QCD calculations and Monte Carlo (MC) event generators, since the measurement of the W mass is directly affected by uncertainties in the p^W_T shape [8,9].

The transverse momentum spectra of W and Z/γ^* bosons produced via the Drell–Yan mechanism have been extensively studied by the Tevatron Collaborations [10–14] and, recently, also by the LHC experiments [15–17]. However, the precision of direct measurements of the Z/γ^* spectrum at low p^Z_T at the LHC and the Tevatron is limited by the experimental resolution and systematic uncertainties rather than by the size of the available data samples. This limitation affects the choice of bin widths and the ultimate precision of the p^Z_T spectrum. In recent years, additional observables with better experimental resolution and smaller sensitivity to experimental systematic uncertainties have been investigated [18–21]. The optimal experimental observable to probe the low-p^Z_T domain of Z/γ^* production was found to be ϕ^*_η which is defined [20] as:

$$\phi^*_\eta \equiv \tan(\phi_\mathrm{acop}/2)\cdot\sin(\theta^*_\eta), \qquad (1)$$

where $\phi_\mathrm{acop} \equiv \pi - \Delta\phi$, $\Delta\phi$ being the azimuthal opening angle between the two leptons, and the angle θ^*_η is a measure of the scattering angle of the leptons with respect to the proton beam direction in the rest frame of the dilepton system. The angle θ^*_η is defined [20] by $\cos(\theta^*_\eta) \equiv \tanh[(\eta^- - \eta^+)/2]$ where η^- and η^+ are the pseudorapidities[1] of the negatively and positively charged lepton, respectively. Therefore, ϕ^*_η depends exclusively on the directions of the two lepton tracks, which are better measured than their momenta. The ϕ^*_η variable is positive by definition. It is correlated to the quantity $p^Z_\mathrm{T}/m_{\ell\ell}$, where $m_{\ell\ell}$ is the invariant mass of the lepton pair, and therefore probes the same physics as the

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal pp interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and the rapidity is defined as $y = \ln[(E+p_z)/(E-p_z)]/2$.

☆☆ Auxiliary figures are available at http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-06/.

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transverse momentum p_T^Z [22]. Values of ϕ_η^* ranging from 0 to 1 probe the p_T^Z distribution mainly up to ~ 100 GeV. The ϕ_η^* distribution of Z/γ^* bosons has been measured in three bins of the Z boson rapidity (y_Z) by the DØ Collaboration using 7.3 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [23].

This Letter presents a measurement of the normalised ϕ_η^* distribution in bins of the Z boson rapidity y_Z using 4.6 fb^{-1} of pp interactions collected at $\sqrt{s} = 7$ TeV in 2011 by the ATLAS detector. The normalised differential cross section is measured in both the electron and muon channels in the fiducial lepton acceptance defined by the lepton ($\ell = e, \mu$) transverse momentum $p_T^\ell > 20$ GeV, the lepton pseudorapidity $|\eta^\ell| < 2.4$ and the invariant mass of the lepton pair 66 GeV $< m_{\ell\ell} <$ 116 GeV. Correction factors allowing the extrapolation of the cross section from the fiducial lepton acceptance to the full lepton acceptance, restricted to 66 GeV $< m_{\ell\ell} <$ 116 GeV, are also presented. The reconstructed ϕ_η^* distribution, after background subtraction, is corrected for all detector effects. The measurements are reported with respect to three distinct reference points at particle level regarding QED final-state radiation (FSR) corrections. The true dilepton mass $m_{\ell\ell}$ and ϕ_η^* are defined by the final-state leptons after QED FSR ("bare" leptons), or by recombining them with radiated photons within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.1$ ("dressed" leptons), or by the final-state leptons before QED FSR ("Born leptons"). The bare definition does not require any QED FSR correction for muons, whilst the dressed definition is the closest to the experimental measurement for electrons. The Born definition corresponds to the full correction for QED FSR effects, so that it can be used for the combination of the electron and muon channels. The combination of the electron and muon channels is compared to QCD predictions obtained by matching resummed and fixed order QCD calculations, as well as to the predictions of MC event generators implementing a parton shower (PS) algorithm.

2. QCD predictions

Non-zero p_T^Z is mainly generated through the emission of partons in the initial state. In the high p_T^Z region ($p_T^Z \gtrsim m_Z$) the spectrum is determined primarily by hard parton emission. Perturbative QCD calculations, based on the truncation of the perturbative series at a fixed order in α_s, are theoretically justified and provide reliable predictions. The inclusive cross-section prediction is finite but the differential cross section diverges as p_T^Z approaches zero. In this limit ($p_T^Z \ll m_Z$) the convergence of the fixed-order expansion is spoiled by the presence of powers of large logarithmic terms which have to be resummed to restore the convergence.

Differential cross sections calculated to $\mathcal{O}(\alpha_s^2)$ are available for Z/γ^* production through the Fewz [24,25] and Dynnlo [26,27] programs. The ResBos [28–30] generator resums the leading contributions up to next-to-next-to-leading logarithms (NNLL) and matches the result to fixed-order calculations at $\mathcal{O}(\alpha_s)$. This is corrected to $\mathcal{O}(\alpha_s^2)$ using a k-factor depending on p_T^Z and y_Z [31]. In addition, the ResBos generator includes a non-perturbative form factor that needs to be determined from data [32]. A slightly different approach has been proposed recently to describe the Tevatron Run II data by matching NNLL accuracy to MCFM calculations [33], with no apparent need for non-perturbative contributions [34,22].

Similarly to resummed calculations, PS algorithms such as those used in Pythia [35] and Herwig [36] provide an all-order approximation of parton radiation in the soft and collinear region through the iterative splitting and radiation of partons. The Powheg [37–40] and Mc@nlo [41] event generators combine next-to-leading order (NLO) QCD matrix elements with a PS algorithm to produce differential cross-section predictions that are finite for all p_T^Z. The Alpgen [42] and Sherpa [43] event generators implement tree-level matrix elements for the generation of multiple hard partons in association with the weak boson. They are matched to parton showers either by a PS algorithm using re-weighting procedures [44,45] or through a veto [42], in order to avoid the double counting of QCD emissions in the matrix element and the parton shower.

3. The ATLAS detector

The ATLAS detector [46] is a multi-purpose particle physics detector operating at one of the beam interaction points of the LHC. It covers nearly the entire solid angle around the collision region and consists of an inner tracking detector (inner detector or ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS).

Measurements in the ID are performed with silicon pixel and microstrip detectors covering $|\eta| < 2.5$. A straw-tube tracking detector follows radially and covers the range $|\eta| < 2.0$. The lead/liquid-argon electromagnetic calorimeter is divided into barrel ($|\eta| < 1.5$) and endcap ($1.4 < |\eta| < 3.2$) sections. The hadronic calorimeter is based on steel/scintillating tiles in the central region ($|\eta| < 1.7$), and is extended to $|\eta| = 4.9$ by endcap and forward calorimeters which use liquid argon. The MS comprises separate trigger and high-precision tracking chambers to measure the deflection of muons in a magnetic field generated by three large superconducting toroids arranged with an eightfold azimuthal coil symmetry around the calorimeters. The high-precision chambers cover a range of $|\eta| < 2.7$. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

4. Event simulation

MC simulations are used to calculate efficiencies and acceptances for the $Z/\gamma^* \to \ell^+\ell^-$ signal processes and to unfold the measured ϕ_η^* spectrum for detector effects and for different levels of QED FSR. The Powheg MC generator is used with CT10 [47] parton distribution functions (PDFs) to generate both the $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ signal events. It is interfaced to Pythia 6.4 with the AUET2B-CTEQ6L1 tune [48] to simulate the parton shower and the underlying event. Generated events are re-weighted as a function of p_T^Z to the predictions from ResBos, which describes the p_T^Z spectrum more accurately [15]. Simulated events are also used to estimate background contributions. The electroweak background processes $W \to \ell\nu$ and $Z/\gamma^* \to \tau^+\tau^-$ are generated using Pythia 6.4. The production of $t\bar{t}$ events is modelled using Mc@nlo and diboson processes are simulated using Herwig. The event generators are interfaced to Photos [49] to simulate QED FSR for all of the simulated samples, except Sherpa which is interfaced to an implementation of the YFS algorithm [50,51].

Multiple interactions per bunch crossing (pile-up) are accounted for by overlaying simulated minimum bias events. To match the observed instantaneous luminosity profile, the simulated events are re-weighted to yield the same distribution of the number of interactions per bunch crossing as measured in the data. The response of the ATLAS detector to the generated particles is modelled using Geant4 [52], and the fully simulated events [53] are passed through the same reconstruction chain as the data. Simulated event samples are corrected for differences with respect to the data in the trigger efficiencies, lepton reconstruction and identification efficiencies as well as in energy (momentum) scale and resolution. The efficiencies are determined by using a

Table 1
The measured normalised differential cross section $1/\sigma^{\text{fid}} \cdot \text{d}\sigma^{\text{fid}}/\text{d}\phi^*_\eta$ in bins of ϕ^*_η for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ channels. The cross sections, which are to be multiplied for convenience by a factor f, are reported with respect to the three different treatments of QED final-state radiation. The relative statistical (δ_{stat}) and total systematic (δ_{sys}) uncertainties are given in percent. The overall point-to-point uncorrelated additional uncertainty in QED FSR of 0.3% is not included.

ϕ^*_η bin range	$Z/\gamma^* \rightarrow e^+e^-$						$Z/\gamma^* \rightarrow \mu^+\mu^-$					
	$1/\sigma^{\text{fid}} \cdot \text{d}\sigma^{\text{fid}}/\text{d}\phi^*_\eta$				δ_{stat} [%]	δ_{sys} [%]	$1/\sigma^{\text{fid}} \cdot \text{d}\sigma^{\text{fid}}/\text{d}\phi^*_\eta$				δ_{stat} [%]	δ_{sys} [%]
	Born	dressed	bare	f			Born	dressed	bare	f		
0.000–0.004	9.77	9.69	9.70	1	0.46	0.35	9.77	9.67	9.67	1	0.39	0.28
0.004–0.008	9.68	9.59	9.59	1	0.47	0.26	9.76	9.66	9.66	1	0.39	0.18
0.008–0.012	9.42	9.36	9.38	1	0.47	0.28	9.42	9.34	9.35	1	0.40	0.24
0.012–0.016	9.14	9.06	9.07	1	0.48	0.35	9.26	9.17	9.18	1	0.40	0.24
0.016–0.020	8.82	8.76	8.77	1	0.49	0.24	8.83	8.76	8.77	1	0.41	0.19
0.020–0.024	8.48	8.43	8.43	1	0.50	0.25	8.51	8.44	8.45	1	0.42	0.27
0.024–0.029	7.97	7.93	7.94	1	0.46	0.26	8.05	8.00	8.01	1	0.39	0.24
0.029–0.034	7.57	7.52	7.53	1	0.47	0.22	7.57	7.52	7.53	1	0.40	0.19
0.034–0.039	7.02	7.00	7.01	1	0.49	0.29	7.11	7.09	7.09	1	0.41	0.17
0.039–0.045	6.55	6.53	6.53	1	0.46	0.22	6.50	6.49	6.49	1	0.39	0.17
0.045–0.051	5.93	5.92	5.92	1	0.48	0.22	6.00	5.99	5.99	1	0.41	0.16
0.051–0.057	5.52	5.52	5.52	1	0.50	0.22	5.52	5.53	5.53	1	0.42	0.22
0.057–0.064	5.04	5.04	5.04	1	0.48	0.22	5.00	5.01	5.01	1	0.41	0.16
0.064–0.072	4.55	4.56	4.56	1	0.48	0.22	4.52	4.52	4.52	1	0.41	0.23
0.072–0.081	4.01	4.03	4.03	1	0.48	0.21	4.04	4.06	4.06	1	0.40	0.18
0.081–0.091	3.58	3.59	3.59	1	0.48	0.22	3.53	3.55	3.55	1	0.41	0.19
0.091–0.102	3.15	3.16	3.16	1	0.49	0.23	3.14	3.16	3.16	1	0.41	0.21
0.102–0.114	2.73	2.74	2.74	1	0.50	0.26	2.73	2.75	2.74	1	0.43	0.23
0.114–0.128	2.34	2.35	2.35	1	0.50	0.29	2.35	2.37	2.37	1	0.42	0.24
0.128–0.145	2.00	2.01	2.01	1	0.49	0.24	2.00	2.01	2.01	1	0.42	0.21
0.145–0.165	1.687	1.697	1.698	1	0.49	0.28	1.669	1.680	1.679	1	0.42	0.28
0.165–0.189	1.355	1.364	1.363	1	0.50	0.25	1.355	1.365	1.365	1	0.43	0.19
0.189–0.219	1.079	1.087	1.087	1	0.50	0.23	1.086	1.093	1.093	1	0.43	0.20
0.219–0.258	8.27	8.34	8.32	10^{-1}	0.50	0.24	8.22	8.28	8.27	10^{-1}	0.43	0.19
0.258–0.312	5.97	6.00	5.99	10^{-1}	0.50	0.25	5.94	5.97	5.97	10^{-1}	0.43	0.17
0.312–0.391	3.97	3.99	3.99	10^{-1}	0.51	0.22	3.94	3.96	3.96	10^{-1}	0.44	0.17
0.391–0.524	2.28	2.28	2.28	10^{-1}	0.52	0.24	2.29	2.29	2.29	10^{-1}	0.45	0.19
0.524–0.695	1.176	1.179	1.177	10^{-1}	0.64	0.29	1.164	1.168	1.166	10^{-1}	0.55	0.23
0.695–0.918	5.79	5.80	5.79	10^{-2}	0.79	0.37	5.77	5.79	5.78	10^{-2}	0.69	0.29
0.918–1.153	2.94	2.95	2.95	10^{-2}	1.07	0.47	2.91	2.91	2.91	10^{-2}	0.95	0.37
1.153–1.496	1.54	1.55	1.54	10^{-2}	1.22	0.52	1.50	1.51	1.51	10^{-2}	1.09	0.41
1.496–1.947	7.25	7.26	7.25	10^{-3}	1.55	0.66	7.05	7.06	7.06	10^{-3}	1.39	0.48
1.947–2.522	3.52	3.51	3.50	10^{-3}	1.97	0.78	3.56	3.56	3.55	10^{-3}	1.74	0.62
2.522–3.277	1.73	1.73	1.72	10^{-3}	2.46	0.96	1.79	1.80	1.80	10^{-3}	2.13	0.71

tag-and-probe method similar to the one described in Section 4.3 of Ref. [54] based on reconstructed Z and W events, while the energy resolution and scale corrections are obtained from a fit to the observed Z boson line shape.

5. Event reconstruction, selection and background estimation

Events recorded during periods with stable beam conditions and passing detector and data-quality requirements are selected. At least one primary vertex reconstructed from at least three tracks is required in each event.

Events in the electron channel are selected online by requiring a single electron candidate with a threshold in transverse momentum p_{T} that was increased during the data-taking from 20 GeV to 22 GeV in response to increased LHC luminosity. Electrons are reconstructed from a cluster of cells with significant energy deposits in the electromagnetic calorimeter matched to an inner detector track. Electron reconstruction uses track refitting with a Gaussian-sum filter to be less sensitive to bremsstrahlung losses and improve the estimates of the electron track parameters [55,56]. The typical angular resolutions in the electron direction measurements are 0.6 mrad for ϕ and 0.0012 for η. The highest and second highest p_{T} electrons are required to have a transverse momentum $p^e_{\text{T}} > 25$ GeV and $p^e_{\text{T}} > 20$ GeV, respectively. The electron pseudorapidity must satisfy $|\eta^e| < 2.4$ with the calorimeter barrel/endcap transition region $1.37 < |\eta^e| < 1.52$ excluded. Electrons are required to pass "medium" identification criteria based on shower shape and track-quality variables, as described in Refs. [57,58]. The criteria are re-optimised for both higher pile-up conditions and higher instantaneous luminosity in 2011.

Events in the muon channel are selected online by a trigger requiring a single muon candidate with $p^{\mu}_{\text{T}} > 18$ GeV. Muons are identified as tracks reconstructed in the muon spectrometer matched to tracks reconstructed in the inner detector and are required to have $p^{\mu}_{\text{T}} > 20$ GeV and $|\eta^{\mu}| < 2.4$. Only isolated muons are selected by requiring the scalar sum of the p_{T} of the tracks within a cone $\Delta R = 0.2$ around the muon to be less than 10% of the muon p_{T}. Muons are required to have a longitudinal impact parameter with respect to the primary vertex less than 10 mm to reduce contributions from cosmic-ray muons and in-time pile-up. In addition, the transverse impact parameter of the track with respect to the primary vertex divided by its uncertainty must be smaller than ten to reduce non-prompt muon backgrounds. The typical angular resolutions in the muon direction measurements are 0.4 mrad for ϕ and 0.001 for η.

$Z/\gamma^* \rightarrow \ell^+\ell^-$ events are selected by requiring two oppositely charged same-flavour leptons with an invariant mass 66 GeV $< m_{\ell\ell} <$ 116 GeV. After these selection requirements $1.22 \cdot 10^6$ di-electron and $1.69 \cdot 10^6$ dimuon candidate events are found in data.

Background contributions from $Z/\gamma^* \rightarrow \tau^+\tau^-$, $W \rightarrow \ell\nu$, $t\bar{t}$ and diboson production are estimated using MC simulations. The cross sections are normalised to next-to-next-to-leading-order (NNLO) predictions for Z/γ^* and W production using Fewz, NLL-NLO predictions for $t\bar{t}$ production [54] and NLO predictions for diboson

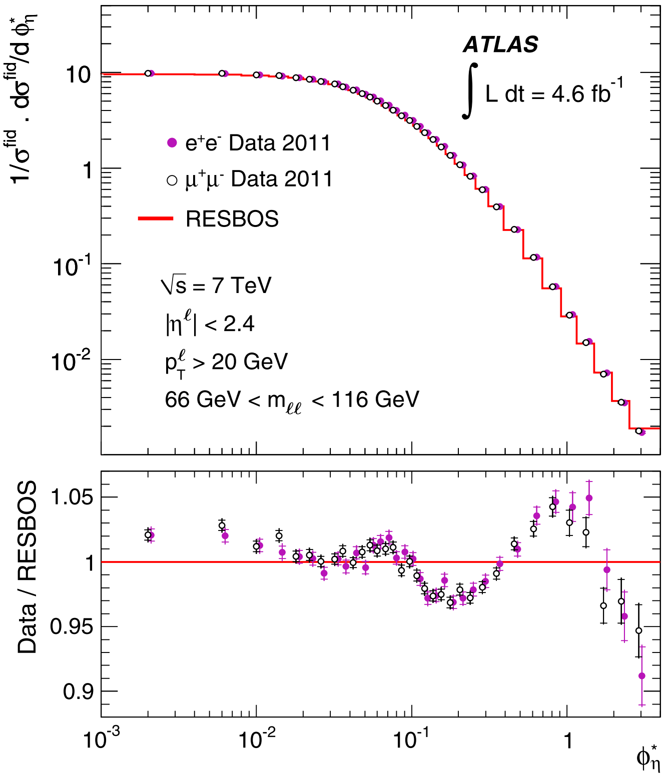

Fig. 1. The measured normalised differential cross section $1/\sigma^{\rm fid} \cdot {\rm d}\sigma^{\rm fid}/{\rm d}\phi^*_\eta$ as a function of ϕ^*_η for $Z/\gamma^* \to e^+e^-$ (closed dots) and $Z/\gamma^* \to \mu^+\mu^-$ (open dots) channels. The measurements are compared to ResBos predictions represented by a line. The ratio of measured cross sections to ResBos predictions is presented in the bottom panel. The measurements are displaced horizontally for better visibility. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The uncertainty due to QED FSR is included in the total uncertainties.

production [59]. For both the e^+e^- and $\mu^+\mu^-$ channels, the main background at high ϕ^*_η values arises from $t\bar{t}$ and diboson production.

At low ϕ^*_η values the background is dominated by multi-jet production, where a jet is falsely identified as a primary e or μ. In this case the background is determined by data-driven methods. A data event sample dominated by jets faking electrons or muons in the final state is employed to determine the shape of the multi-jet background. For the e^+e^- channel, the multi-jet sample is obtained from electrons failing the medium identification criteria. In order to assess systematic uncertainties in the shape of the multi-jet background, an alternative multi-jet control sample was also selected using non-isolated electrons. For the $\mu^+\mu^-$ channel, the multi-jet sample is extracted by inverting the isolation requirement on muons. The uncertainty in its shape was studied by comparing same-sign and opposite-sign dimuon events. The normalisation of this multi-jet background template is determined by adjusting the sum of it and other background and signal MC predictions to data as a function of the invariant mass spectrum of the dilepton pair. An extended dilepton mass range, 50 GeV $< m_{\ell\ell} <$ 150 GeV (200 GeV for electrons), was employed to better constrain the off-resonance region and improve the accuracy of the multi-jet background normalisation.

The total fraction of background events is $(0.61 \pm 0.31)\%$ in the e^+e^- channel and $(0.56 \pm 0.28)\%$ in the $\mu^+\mu^-$ channel. The multi-jet background represents $\sim 50\%$ of the total background in both channels and dominates at low ϕ^*_η values. An irreducible background may also arise from the production of a lepton pair

Table 2
The combined normalised differential cross section $1/\sigma^{\rm fid} \cdot {\rm d}\sigma^{\rm fid}/{\rm d}\phi^*_\eta$ in bins of ϕ^*_η at Born level. The statistical ($\delta_{\rm stat}$) and total systematic ($\delta_{\rm sys}$) uncertainties are given in percent. The normalised differential cross section extrapolated to the full lepton acceptance $1/\sigma^{\rm tot} \cdot {\rm d}\sigma^{\rm tot}/{\rm d}\phi^*_\eta$ is obtained at Born level by multiplication with the inverse acceptance correction factor A_c^{-1}. The uncertainty $\delta(A_c^{-1})$ on this acceptance correction factor is also given in percent. The overall point-to-point uncorrelated additional uncertainty in QED FSR of 0.3% is not included.

ϕ^*_η bin range	$1/\sigma^{\rm fid} \cdot {\rm d}\sigma^{\rm fid}/{\rm d}\phi^*_\eta$	$\delta_{\rm stat}$ [%]	$\delta_{\rm sys}$ [%]	A_c^{-1}	$\delta(A_c^{-1})$ [%]
0.000–0.004	9.77	0.30	0.21	1.06	3.8
0.004–0.008	9.73	0.30	0.20	1.06	3.0
0.008–0.012	9.41	0.31	0.18	1.06	3.7
0.012–0.016	9.21	0.31	0.22	1.06	2.4
0.016–0.020	8.82	0.31	0.16	1.05	2.5
0.020–0.024	8.49	0.32	0.18	1.05	2.2
0.024–0.029	8.01	0.29	0.18	1.05	1.8
0.029–0.034	7.56	0.30	0.14	1.04	2.4
0.034–0.039	7.07	0.31	0.15	1.04	2.2
0.039–0.045	6.52	0.30	0.14	1.03	2.2
0.045–0.051	5.97	0.31	0.13	1.02	2.8
0.051–0.057	5.52	0.32	0.16	1.01	2.1
0.057–0.064	5.02	0.31	0.13	1.01	1.9
0.064–0.072	4.54	0.31	0.18	1.00	2.0
0.072–0.081	4.03	0.31	0.13	0.99	1.8
0.081–0.091	3.56	0.31	0.15	0.99	1.0
0.091–0.102	3.15	0.32	0.16	0.98	1.1
0.102–0.114	2.731	0.32	0.17	0.97	1.3
0.114–0.128	2.347	0.32	0.19	0.97	1.3
0.128–0.145	1.996	0.32	0.16	0.96	1.7
0.145–0.165	1.677	0.32	0.19	0.95	2.0
0.165–0.189	1.355	0.32	0.16	0.95	2.7
0.189–0.219	1.084	0.32	0.15	0.94	2.3
0.219–0.258	$8.24 \cdot 10^{-1}$	0.33	0.15	0.94	2.9
0.258–0.312	$5.95 \cdot 10^{-1}$	0.33	0.14	0.93	2.9
0.312–0.391	$3.96 \cdot 10^{-1}$	0.33	0.14	0.92	3.4
0.391–0.524	$2.282 \cdot 10^{-1}$	0.34	0.15	0.92	3.5
0.524–0.695	$1.169 \cdot 10^{-1}$	0.42	0.18	0.92	4.4
0.695–0.918	$5.78 \cdot 10^{-2}$	0.52	0.23	0.93	4.0
0.918–1.153	$2.92 \cdot 10^{-2}$	0.71	0.29	0.94	5.3
1.153–1.496	$1.52 \cdot 10^{-2}$	0.81	0.33	0.98	10.5
1.496–1.947	$7.13 \cdot 10^{-3}$	1.04	0.40	1.04	10.3
1.947–2.522	$3.54 \cdot 10^{-3}$	1.30	0.49	1.11	17.5
2.522–3.277	$1.77 \cdot 10^{-3}$	1.61	0.58	1.19	16.2

via photon-photon interactions, $\gamma\gamma \to \ell^+\ell^-$. This contribution was evaluated at leading order using FEWZ 3.1 [24,60] and the MRST2004qed [61] PDF, currently the only available PDF set containing a description of the QED part of the proton. According to the LO cross section calculated in the fiducial lepton acceptance, the fraction of photon-induced events is expected to be below 0.1%, with an uncertainty of 50%. This contribution is six times lower than the sum of other background contributions and is therefore neglected.

6. Cross-section measurement and systematic uncertainties

The differential cross section is evaluated in bins of ϕ^*_η, or of (ϕ^*_η, y_Z), from the number of observed data events in each bin after subtraction of the estimated number of background events.

A bin-by-bin correction is used to correct the observed data for detector acceptances and inefficiencies, as well as for QED FSR. The correction factors are determined using signal MC events. For the chosen bin widths the purity, defined as the fraction of simulated events reconstructed in a ϕ^*_η bin which have generator-level ϕ^*_η in the same bin, is always more than 83% and reaches 98% in the highest ϕ^*_η bins. In each bin, the data are normalised to the cross section integrated over the fiducial acceptance region.

An analysis of systematic uncertainties was performed, in which the sensitivity of the measurements to variations in the efficiencies and energy scales of the detector components and to the details of the correction procedure is tested. The systematic uncertainties in the measured cross section are determined by repeating the analysis after applying appropriate variations for each source of systematic uncertainty to the simulated samples. The systematic uncertainties which are correlated between ϕ^*_η bins are listed below.

- Uncertainties in the estimation of the number of background events from multi-jet, $W \to \ell\nu$ and $Z/\gamma^* \to \tau^+\tau^-$ decays, $t\bar{t}$ and diboson processes yield values of up to 0.3% in the e^+e^- and $\mu^+\mu^-$ channels, when propagated to the normalised differential cross section.
- Possible mis-modelling of the angular resolution of tracking detectors leads to uncertainties of up to 0.3% (0.2%) on the normalised differential cross section in the e^+e^- ($\mu^+\mu^-$) channel.
- The dependence of the bin-by-bin correction factors on the shape of the assumed ϕ^*_η distribution was tested by re-weighting simulated events to the measured ϕ^*_η cross section. An iterative Bayesian unfolding technique [62] was employed as an alternative approach to assess systematic uncertainties. The uncertainty in the correction procedure is found to be smaller than 0.1% in both channels and for the full ϕ^*_η range.
- As the definition of the ϕ^*_η variable is based on the lepton angles, the normalised differential cross section depends only weakly on uncertainties in the lepton energy/momentum scale and resolution. When propagated to the normalised differential cross section, these uncertainties amount to less than 0.1% and 0.03% in the e^+e^- and $\mu^+\mu^-$ channels, respectively.
- Uncertainties arising from the mis-modelling of lepton identification efficiencies and trigger efficiencies in the simulation amount respectively to 0.05% (0.03%) and 0.04% (0.02%) in the e^+e^- ($\mu^+\mu^-$) channel.
- Pile-up has only a weak influence on this measurement and results in an uncertainty of at most 0.05% on the normalised differential cross section.

A second class of systematic uncertainties, listed below, are considered uncorrelated across ϕ^*_η bins.

- Uncertainties on the bin-by-bin correction factors arising from the MC sample statistics are 0.2% (0.13%) at low ϕ^*_η in the e^+e^- ($\mu^+\mu^-$) channel, increasing to 0.9% (0.6%) in the highest ϕ^*_η bins.
- Possible local biases in angular measurements (ϕ, η) by tracking detectors yield an estimated constant uncertainty of 0.1% on the normalised differential cross section. The local effect of these biases allows bin-to-bin correlations to be neglected. The impact of this assumption on the combination of electron and muon channel results is small.
- A conservative systematic uncertainty of 0.3% due to ϕ^*_η-dependent modelling of QED FSR is assigned by comparing predictions from Photos [49] and from the Sherpa implementation of the YFS algorithm [50,51]. This comparison provides the size of the uncertainty but however does not allow the shape of the ϕ^*_η dependence to be estimated. This uncertainty was therefore treated as uncorrelated across ϕ^*_η bins. The uncertainty is assumed to hold for cross sections at Born, dressed and bare levels and for both electron and muon channel measurements. It therefore does not affect the combination of them.

The total systematic uncertainty on each data point is formed by adding the individual contributions in quadrature.

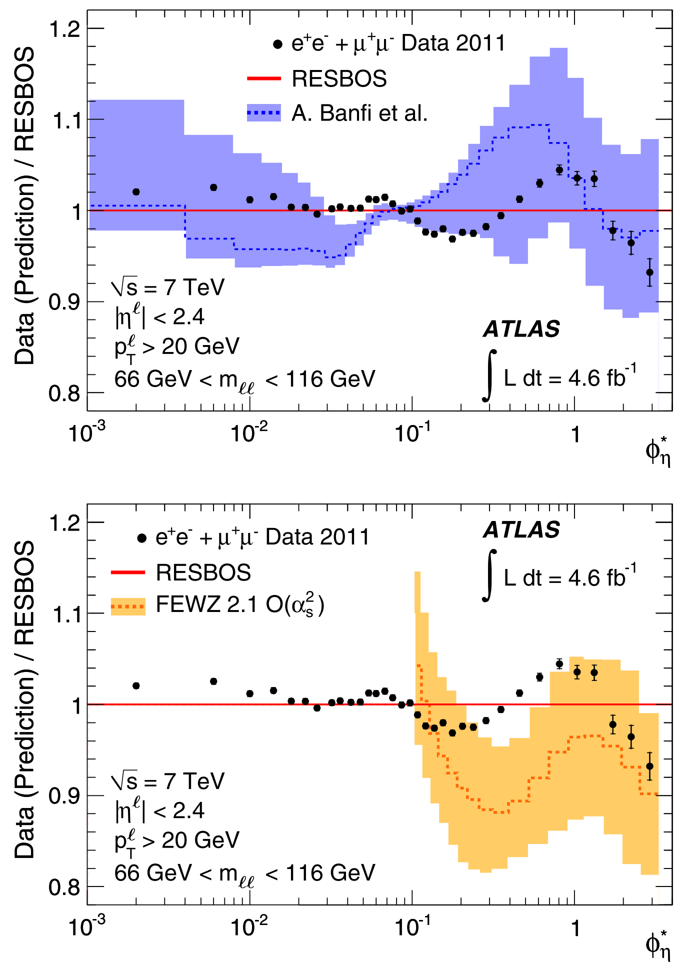

Fig. 2. The ratio of the combined normalised differential cross section $1/\sigma^{\text{fid}} \cdot d\sigma^{\text{fid}}/d\phi^*_\eta$ to ResBos predictions as a function of ϕ^*_η. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The uncertainty due to QED FSR is included in the total uncertainties. The measurements are also compared to predictions, which are represented by a dashed line, from Ref. [22] and from Fewz in the top and bottom panels, respectively. Uncertainties associated with these two calculations are represented by shaded bands. The prediction from Fewz is only presented for $\phi^*_\eta > 0.1$.

7. Results and discussion

The normalised differential cross sections measured for $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ production in the fiducial acceptance are presented in Table 1. The measurements are reported with respect to the Born, dressed and bare reference points at particle level regarding QED FSR. The QED FSR corrections for the three levels are calculated using Photos. The measured cross sections defined at the Z/γ^* Born level are shown in Fig. 1 for the e^+e^- and $\mu^+\mu^-$ channels and are compared to predictions from ResBos.

The normalised differential cross sections measured in the fiducial acceptance for the two channels are combined using a χ^2 minimisation method which takes into account the point-to-point correlated and uncorrelated systematic uncertainties [63–65] and correlations between electron and muon channels. The procedure allows a model independent check of the electron and muon data consistency and leads to a significant reduction of the correlated uncertainties. The uncertainties due to the unfolding procedure, the pile-up, and QED FSR are considered to be completely correlated between the e^+e^- and $\mu^+\mu^-$ channels. The minimisation yields a total χ^2 per degree of freedom (n_{dof})

Table 3
The combined normalised differential cross section $1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$ in bins of ϕ^*_η and in three $|y_Z|$ ranges. The statistical (δ_{stat}) and total systematic (δ_{sys}) uncertainties are given in percent. The overall point-to-point uncorrelated additional uncertainty in QED FSR of 0.3% is not included.

ϕ^*_η bin range	$\lvert y_Z\rvert < 0.8$			$0.8 \leqslant \lvert y_Z\rvert < 1.6$			$\lvert y_Z\rvert \geqslant 1.6$		
	$1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$	δ_{stat} [%]	δ_{sys} [%]	$1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$	δ_{stat} [%]	δ_{sys} [%]	$1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$	δ_{stat} [%]	δ_{sys} [%]
0.000–0.004	9.73	0.45	0.25	9.81	0.48	0.21	9.79	0.75	0.33
0.004–0.008	9.65	0.45	0.23	9.81	0.48	0.26	9.77	0.75	0.35
0.008–0.012	9.37	0.46	0.24	9.45	0.49	0.23	9.45	0.76	0.30
0.012–0.016	9.12	0.46	0.24	9.31	0.49	0.25	9.25	0.77	0.38
0.016–0.020	8.81	0.47	0.21	8.88	0.50	0.22	8.72	0.79	0.31
0.020–0.024	8.49	0.48	0.20	8.48	0.51	0.25	8.52	0.80	0.38
0.024–0.029	7.99	0.44	0.23	8.05	0.47	0.21	7.99	0.74	0.29
0.029–0.034	7.54	0.46	0.21	7.64	0.48	0.19	7.45	0.77	0.28
0.034–0.039	7.12	0.47	0.19	7.07	0.50	0.21	6.99	0.79	0.31
0.039–0.045	6.53	0.45	0.18	6.57	0.47	0.19	6.38	0.75	0.27
0.045–0.051	5.92	0.47	0.18	6.01	0.50	0.19	6.02	0.78	0.28
0.051–0.057	5.52	0.48	0.20	5.50	0.52	0.21	5.53	0.81	0.30
0.057–0.064	5.06	0.47	0.18	5.00	0.50	0.19	4.97	0.79	0.28
0.064–0.072	4.53	0.46	0.22	4.53	0.49	0.21	4.56	0.77	0.30
0.072–0.081	4.02	0.46	0.19	4.04	0.49	0.18	4.02	0.77	0.27
0.081–0.091	3.56	0.47	0.19	3.55	0.50	0.20	3.55	0.78	0.27
0.091–0.102	3.15	0.47	0.20	3.14	0.50	0.21	3.15	0.79	0.28
0.102–0.114	2.72	0.49	0.20	2.73	0.52	0.21	2.75	0.81	0.29
0.114–0.128	2.34	0.48	0.22	2.34	0.52	0.22	2.37	0.81	0.31
0.128–0.145	2.00	0.47	0.19	2.00	0.51	0.22	1.99	0.80	0.27
0.145–0.165	1.667	0.48	0.20	1.677	0.51	0.21	1.707	0.80	0.38
0.165–0.189	1.342	0.49	0.19	1.356	0.52	0.21	1.385	0.81	0.28
0.189–0.219	1.073	0.49	0.19	1.085	0.52	0.19	1.112	0.81	0.28
0.219–0.258	$8.18 \cdot 10^{-1}$	0.49	0.18	$8.22 \cdot 10^{-1}$	0.52	0.19	$8.47 \cdot 10^{-1}$	0.81	0.28
0.258–0.312	$5.96 \cdot 10^{-1}$	0.49	0.18	$5.87 \cdot 10^{-1}$	0.53	0.19	$6.13 \cdot 10^{-1}$	0.81	0.26
0.312–0.391	$3.95 \cdot 10^{-1}$	0.50	0.18	$3.89 \cdot 10^{-1}$	0.54	0.19	$4.14 \cdot 10^{-1}$	0.82	0.26
0.391–0.524	$2.28 \cdot 10^{-1}$	0.50	0.20	$2.25 \cdot 10^{-1}$	0.55	0.20	$2.36 \cdot 10^{-1}$	0.84	0.28
0.524–0.695	$1.174 \cdot 10^{-1}$	0.62	0.24	$1.151 \cdot 10^{-1}$	0.67	0.25	$1.21 \cdot 10^{-1}$	1.03	0.34
0.695–0.918	$5.88 \cdot 10^{-2}$	0.77	0.30	$5.70 \cdot 10^{-2}$	0.84	0.31	$5.69 \cdot 10^{-2}$	1.32	0.42
0.918–1.153	$3.05 \cdot 10^{-2}$	1.04	0.40	$2.87 \cdot 10^{-2}$	1.15	0.42	$2.67 \cdot 10^{-2}$	1.86	0.58
1.153–1.496	$1.62 \cdot 10^{-2}$	1.17	0.44	$1.50 \cdot 10^{-2}$	1.30	0.47	$1.29 \cdot 10^{-2}$	2.21	0.71
1.496–1.947	$7.67 \cdot 10^{-3}$	1.50	0.56	$7.08 \cdot 10^{-3}$	1.65	0.58	$5.66 \cdot 10^{-3}$	2.91	0.95
1.947–2.522	$4.08 \cdot 10^{-3}$	1.83	0.70	$3.53 \cdot 10^{-3}$	2.06	0.69	$2.00 \cdot 10^{-3}$	4.35	1.39
2.522–3.277	$2.10 \cdot 10^{-3}$	2.22	0.80	$1.70 \cdot 10^{-3}$	2.59	0.87	$9.66 \cdot 10^{-4}$	5.39	1.92

of $\chi^2/n_{\text{dof}} = 33.2/34$, indicating a good consistency between the electron and muon data. Measured values of the combined normalised differential cross section $1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$ within the fiducial lepton acceptance are presented in Table 2. At lower ϕ^*_η values the statistical and systematic uncertainties are of the same order, whilst for large ϕ^*_η values statistical uncertainties are dominating. The acceptance correction factors A_c needed to extrapolate the measurement to the full lepton acceptance are determined using the Powheg simulation with the CT10 PDF set and re-weighted as a function of p_T^Z to ResBos predictions. The uncertainty in A_c is estimated from the extreme differences among predictions obtained with ResBos, Mc@nlo, Sherpa, Alpgen, Herwig and Powheg interfaced to Pythia8. Uncertainties in A_c resulting from PDF uncertainties are below 1%.

The ratio of the combined normalised differential cross section to the ResBos prediction is shown as a function of ϕ^*_η in Fig. 2. The measurement is also compared to a QCD calculation by A. Banfi et al. [22] and to another obtained with Fewz 2.1. The ratios of these two calculations to ResBos predictions are also shown in Fig. 2. The CTEQ6m [66] PDF set is used in the calculation of Ref. [22]. The theoretical uncertainties on this calculation are evaluated by varying the resummation, renormalisation and factorisation scales μ_Q, μ_R and μ_F between $m_Z/2$ and $2m_Z$, with the constraints $0.5 \leqslant \mu_i/\mu_j \leqslant 2$, where $i, j \in \{F, Q, R\}$, and $\mu_F/\mu_Q \geqslant 1$. Uncertainties coming from the PDFs are also considered [22]. For Fewz, the CT10 PDF set is used. Uncertainties are evaluated by varying μ_R and μ_F by factors of two around the nominal scale m_Z with the constraint $0.5 \leqslant \mu_R/\mu_F \leqslant 2$, by varying α_s within a range corresponding to 90% confidence-level (CL) limits [67], and by using the PDF error eigenvector sets.

The difference between the ResBos prediction and data is $\sim 2\%$ for $\phi^*_\eta < 0.1$, increasing to 5% for higher ϕ^*_η values. This difference is smaller than the uncertainty in ResBos predictions due to the propagation of PDF eigenvectors sets, which amounts to 4% for $\phi^*_\eta < 0.1$ and 6% above. The description of data provided by calculations from A. Banfi et al. [22] is less good than ResBos but observed differences remain within the theoretical uncertainties of the calculation. The prediction obtained with Fewz undershoots the data by $\sim 10\%$, as already observed for the p_T^Z spectrum in Ref. [15]. At low ϕ^*_η values, corresponding mainly to low p_T^Z, fixed-order perturbative QCD calculations are not expected to give an adequate description of the cross section. The prediction from Fewz is therefore only presented for $\phi^*_\eta > 0.1$. It is normalised using the total cross section predicted by Fewz, which accurately describes experimental measurements [58].

The cross section is also measured double differentially in bins of ϕ^*_η for three independent bins of $|y_Z|$ for both the e^+e^- and $\mu^+\mu^-$ channels. The double differential cross-section measurements in the two channels are combined using the same χ^2 minimisation procedure as used for the single differential cross section. The minimisation yields a total $\chi^2/n_{\text{dof}} = 118/102$. Measured values of the combined normalised differential cross section $1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$ within the fiducial lepton acceptance in all ϕ^*_η and $|y_Z|$ bins are presented in Table 3.

The ratio of the combined normalised differential cross section to the ResBos prediction is shown as a function of ϕ^*_η for the three $|y_Z|$ ranges in Fig. 3. The measurement is also compared

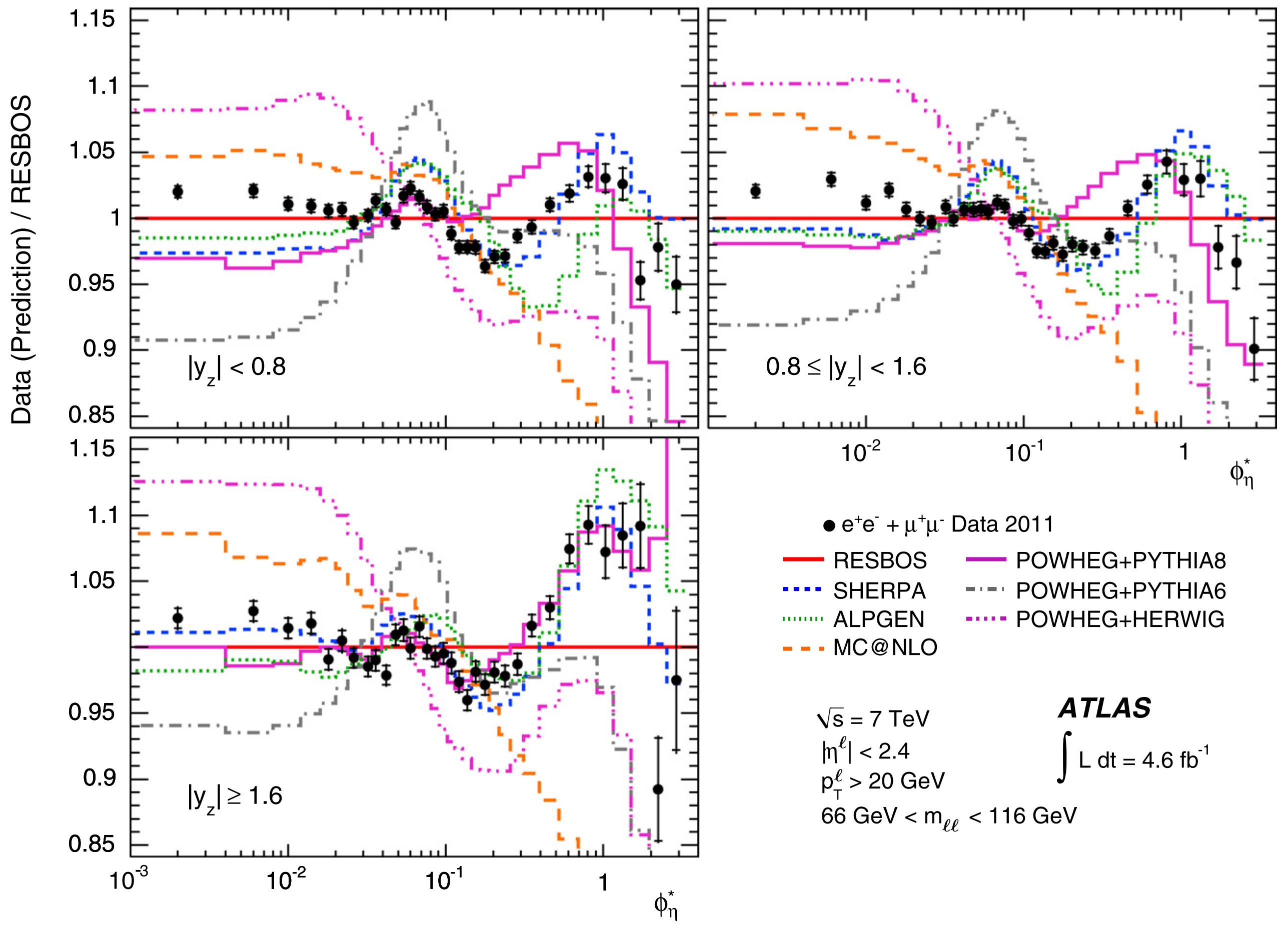

Fig. 3. The ratio of the combined normalised differential cross section $1/\sigma^{\text{fid}} \cdot \mathrm{d}\sigma^{\text{fid}}/\mathrm{d}\phi^*_\eta$ to the ResBos predictions as a function of ϕ^*_η in three ranges of $|y_Z|$. The inner and outer error bars on the data points represent the statistical and total uncertainties, respectively. The uncertainty due to QED FSR is included in the total uncertainties. The measurements are also compared to predictions from different MC event generators.

to predictions obtained using different MC event generators. The PDF set CT10 is employed in all calculations, except for Alpgen where the CTEQ6L1 PDF set is used. The parton-shower parameters of each MC generator are set to their default values, except for Pythia6 where a specific ATLAS re-tuning was used [48]. The generators Alpgen, interfaced to Herwig, and Sherpa provide a good description of the spectrum for $\phi^*_\eta > 0.1$. In particular, Sherpa describes the data better than ResBos over all $|y_Z|$ bins for $\phi^*_\eta > 0.1$. However, for $\phi^*_\eta < 0.1$ the deviations of Sherpa or Alpgen from the data are $\sim 5\%$, somewhat larger than those of ResBos. The Powheg generator interfaced to Pythia8 is also able to describe the data to within 5% over the whole ϕ^*_η range.

The effect of changing the PS tunings and algorithms interfaced to Powheg was investigated by using Pythia6 and Herwig interfaced to the same Powheg NLO calculation. These two variations give a worse description of data than Pythia8, and deviations from data of $\sim 10\%$ are observed. The Mc@nlo generator interfaced to Herwig does not properly describe the data for $\phi^*_\eta > 0.1$, and deviations from data of the order of 4–7% are observed for $\phi^*_\eta < 0.1$ depending on the $|y_Z|$ bin. The level of agreement between MC generators and data is very similar for comparisons at the dressed level.

8. Conclusion

A measurement of the ϕ^*_η distribution of Z/γ^* boson candidates in $\sqrt{s} = 7$ TeV pp collisions at the LHC is presented. The data were collected with the ATLAS detector and correspond to an integrated luminosity of 4.6 fb^{-1}. Normalised differential cross sections as a function of ϕ^*_η have been measured in bins of the Z boson rapidity y_Z up to $\phi^*_\eta \sim 3$ for electron and muon pairs with an invariant mass 66 GeV $< m_{\ell\ell} <$ 116 GeV. The high number of Z/γ^* boson candidates recorded permits the use of finer bins as compared to a similar study performed at the Tevatron. The typical uncertainty achieved by the combination of electron and muon data integrated over the whole Z rapidity range is below 0.5% for $\phi^*_\eta < 0.5$ increasing to 0.8% at larger ϕ^*_η values.

The cross-section measurements have been compared to resummed QCD predictions combined with fixed-order perturbative QCD calculations. Calculations using ResBos provide the best descriptions of the data. However, they are unable to reproduce the detailed shape of the measured cross section to better than 4%.

The cross-section measurements have also been compared to predictions from different Monte Carlo generators interfaced to a parton shower algorithm. The best descriptions of the measured ϕ^*_η spectrum are provided by Sherpa and Powheg+Pythia8 Monte Carlo event generators. For ϕ^*_η values above 0.1, predictions from Sherpa are able to reproduce the data to within $\sim 2\%$. The low ϕ^*_η part of the spectrum is, however, described less accurately than by ResBos. Double differential measurements as a function of ϕ^*_η and y_Z provide valuable information for the tuning of MC generators. None of the tested predictions is able to reproduce the detailed shape of the measured cross section within the experimental precision reached, which is typically lower by one order of magnitude than present theoretical uncertainties.

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