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

ATLAS Collaboration*

A measurement of angular correlations in Drell–Yan lepton pairs via the $\phi_2^\ell$ observable is presented. This variable probes the same physics as the $Z/\gamma^*$ 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 $\phi_2^\ell$ 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 $\phi_2^\ell$ 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.

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1. Introduction

In hadron collisions at TeV energies the vector bosons $W$ and $Z/\gamma^*$ 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 $p_T$ spectrum ($p_T^Z < m_Z$), 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 $Z/\gamma^*$ boson cross section is valid also for the Higgs boson [4–7]. A precise understanding of the $p_T^Z$ 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 $p_T^W$ shape [8,9].

The transverse momentum spectra of $W$ and $Z/\gamma^*$ 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 $Z/\gamma^*$ spectrum at low $p_T^Z$ 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 $p_T^Z$ 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-$p_T^Z$ domain of $Z/\gamma^*$ production was found to be $\phi_2^\ell$ which is defined [20] as:

$$\phi_2^\ell \equiv \tan(\phi_{acop}/2) \cdot \sin(\phi_{acop}^\eta),$$

(1)

where $\phi_{acop} \equiv \pi - \Delta\phi$, $\Delta\phi$ being the azimuthal opening angle between the two leptons, and the angle $\phi_{acop}^\eta$ 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 $\phi_{acop}^\eta$ is defined [20] by $\cos(\phi_{acop}^\eta) \equiv \tan((\eta^- - \eta^+)/2)$ where $\eta^-$ and $\eta^+$ are the pseudorapidities of the negatively and positively charged lepton, respectively. Therefore, $\phi_2^\ell$ depends exclusively on the direction of the two lepton tracks, which are better measured than their momenta. The $\phi_2^\ell$ variable is positive by definition. It is correlated to the quantity $p_T^{Z}/m_{\ell\ell}$, where $m_{\ell\ell}$ is the invariant mass of the lepton pair, and therefore probes the same physics as the $p_T^Z$ spectrum.
transverse momentum $p_T^Z$ [22]. Values of $\phi_R^\ast$ ranging from 0 to 1 probe the $p_T^Z$ distribution mainly up to \( \sim 100 \) GeV. The $\phi_R^\ast$ distribution of $Z/\gamma^*\rightarrow e^+e^-$ bosons has been measured in three bins of the $Z$ boson rapidity ($y_Z$) by the D0 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 $\phi_R^\ast$ distribution in bins of the $Z$ boson rapidity $y_Z$ using 4.6 fb$^{-1}$ of $p\bar{p}$ 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 $\phi_R^\ast$ 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 spectrum, after background subtraction, is corrected for all detector effects and consists of an inner tracking detector (inner detector or ID) surrounding the beam pipe, a calorimeter, 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.

### 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 microstrip detectors covering the range $|\eta| < 2.5$. The ATLAS 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 $Z/\gamma^*\rightarrow e^+e^-$ signal processes and to unfold the measured $\phi_R^\ast$ 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 $Z/\gamma^*\rightarrow e^+e^-$ and $Z/\gamma^*\rightarrow \mu^+\mu^-$ signal events. It is interfaced to Pythia 6.4 with the AUE2B-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 $W \rightarrow t\ell$ and $Z/\gamma^*\rightarrow t\bar{t}$ 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
Rapidity must satisfy $\phi^*_e$ 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 $J$, are reported with respect to the three different treatments of QED final-state radiation. The relative statistical ($\delta_{\text{stat}}$) and total systematic ($\delta_{\text{sys}}$) uncertainties are given in percent. The overall point-to-point uncorrelated additional uncertainty in QED FSR of 0.3% is not included.

Events in the electron channel are selected online by requiring $p_T^e > 18$ GeV and $|\eta^e| < 2.4$. 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 0.1 cm 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 10 mm to reduce non-prompt muon backgrounds. The typical angular resolutions in the muon direction measurements are $0.4 \text{ mrad}$ for $\phi^* \mu^-$ and 0.001 for $|\eta| < 2.2$. Fewz predictions for diboson production [54] and NLO predictions for diboson production using Ftwz, NLL-NLO predictions for $t\bar{t}$ production [54] and NLO predictions for diboson

<table>
<thead>
<tr>
<th>$\phi^*_e$ bin range</th>
<th>$Z/\gamma^* \rightarrow e^+e^-$</th>
<th>$Z/\gamma^* \rightarrow \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/\sigma^\text{fid}/d\phi^*_e$</td>
<td>$\sigma^\text{fid}/d\phi^*_e$</td>
<td>$\sigma^\text{fid}/d\phi^*_e$</td>
</tr>
<tr>
<td>$\delta_{\text{stat}}$</td>
<td>$\delta_{\text{sys}}$</td>
<td>$\delta_{\text{stat}}$</td>
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<td>$1/\sigma^\text{fid}/d\phi^*_e$</td>
<td>$\sigma^\text{fid}/d\phi^*_e$</td>
<td>$\sigma^\text{fid}/d\phi^*_e$</td>
</tr>
<tr>
<td>$\delta_{\text{stat}}$</td>
<td>$\delta_{\text{sys}}$</td>
<td>$\delta_{\text{stat}}$</td>
</tr>
</tbody>
</table>

| $0.000-0.004$ | $0.77$ | $69.69$ | $79.90$ | $1$ | $0.46$ | $0.35$ | $0.39$ | $0.28$ |
| $0.004-0.008$ | $0.98$ | $95.99$ | $99.59$ | $1$ | $0.47$ | $0.26$ | $0.39$ | $0.18$ |
| $0.000-0.012$ | $0.94$ | $93.96$ | $93.93$ | $1$ | $0.47$ | $0.27$ | $0.40$ | $0.24$ |
| $0.000-0.012$ | $0.94$ | $93.96$ | $93.93$ | $1$ | $0.47$ | $0.27$ | $0.40$ | $0.24$ |
| $0.016-0.020$ | $0.82$ | $87.68$ | $87.87$ | $1$ | $0.49$ | $0.24$ | $0.41$ | $0.24$ |
| $0.016-0.020$ | $0.82$ | $87.68$ | $87.87$ | $1$ | $0.49$ | $0.24$ | $0.41$ | $0.24$ |
| $Z/\gamma^* \rightarrow e^+e^-$ | $Z/\gamma^* \rightarrow \mu^+\mu^-$ |

Events recorded during periods with stable beam conditions are identified as tracks reconstructed in the muon spectrometer matched to tracks reconstructed in the inner detector and are required to have $p_T^\mu > 20$ GeV and $|\eta^\mu| < 2.4$. The measured normalised differential cross section is obtained from a fit to the 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 $p_T^\mu > 18$ GeV. Muons are identified as tracks reconstructed in the muon spectrometer matched to tracks reconstructed in the inner detector and are required to have $p_T^\mu > 20$ 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 0.1 cm 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 10 mm to reduce non-prompt muon backgrounds. The typical angular resolutions in the muon direction measurements are $0.4 \text{ mrad}$ for $\phi^* \mu^-$ and 0.001 for $|\eta| < 2.2$.

$Z/\gamma^* \rightarrow e^+e^-$ events are selected by requiring two oppositely charged same-flavour leptons with an invariant mass $66 \text{ GeV} < m_{ee} < 116 \text{ GeV}$. After these selection requirements, 106 dimuon candidate events are found in data. Background contributions from $Z/\gamma^* \rightarrow \tau^+\tau^-$, $W \rightarrow \ell\nu$ and $t\bar{t}$ and diboson production are estimated using MC simulations. The cross sections are normalised to next-to-next-to-leading-order (NNLO) predictions for $Z/\gamma^*$ and $W$ production using Ftwz, NLL-NLO predictions for $t\bar{t}$ production [54] and NLO predictions for diboson...
production [59]. For both the $e^+e^-$ and $\mu^+\mu^-$ channels, the background at high $\phi^*_\eta$ values arises from $t\bar{t}$ and diboson production via photon-photon interactions, $\gamma\gamma \rightarrow \ell^+\ell^-$. 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 $\phi^*_\eta$, or of $(\phi^*_\eta, y_T)$, 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 any bin widths the purity, defined as the fraction of simulated events reconstructed in a $\phi^*_\eta$ bin which have generator-level $\phi^*_\eta$ in the same bin, is always more than 83% and reaches 98% in the highest $\phi^*_\eta$ 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

<table>
<thead>
<tr>
<th>$\phi^*_\eta$ range</th>
<th>$1/\sigma^{fid} \cdot d\sigma^{fid}/d\phi^*_\eta$</th>
<th>$\delta_{stat}$ [%]</th>
<th>$\delta_{sys}$ [%]</th>
<th>$A_{\gamma\gamma}^{-1}$</th>
<th>$\delta(A_{\gamma\gamma}^{-1})$ [%]</th>
</tr>
</thead>
<tbody>
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<td>0.000–0.004</td>
<td>9.77</td>
<td>0.30</td>
<td>0.21</td>
<td>1.06</td>
<td>3.8</td>
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<td>0.008–0.012</td>
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<td>0.18</td>
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<td>0.020–0.024</td>
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<td>1.30</td>
<td>0.49</td>
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<td>2.522–3.277</td>
<td>1.77 $10^{-3}$</td>
<td>1.61</td>
<td>0.58</td>
<td>1.19</td>
<td>16.2</td>
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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 $\phi_\eta^*$ bins are listed below.

- Uncertainties in the estimation of the number of background events from multi-jet, $W \rightarrow \ell \nu$ and $Z/\gamma^* \rightarrow \tau^+ \tau^-$ 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 $\phi_\eta^*$ distribution was tested by re-weighting simulated events to the measured $\phi_\eta^*$ 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 $\phi_\eta^*$ range.
- As the definition of the $\phi_\eta^*$ 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 0.3% 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 $\phi_\eta^*$ bins.

- Uncertainties on the bin-by-bin correction factors arising from the MC sample statistics are 0.2% (0.13%) at low $\phi_\eta^*$ in the $e^+e^-$ ($\mu^+\mu^-$) channel, increasing to 0.9% (0.6%) in the highest $\phi_\eta^*$ bins.
- Possible local biases in angular measurements ($\phi$, $\eta$) 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 $\phi_\eta^*$-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 $\phi_\eta^*$ dependence to be estimated. This uncertainty was therefore treated as uncorrelated across $\phi_\eta^*$ bins. The uncertainty is assumed to hold for cross sections at 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 $Z/\gamma^*$ Born level are shown in Fig. 1 for the $e^+e^-$ and $\mu^+\mu^-$ channels and are compared to predictions from ResBos.

7. Results and discussion

The normalised differential cross sections measured for $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ 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 $Z/\gamma^*$ 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 $\chi^2$ 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 $\chi^2$ per degree of freedom ($n_{dof}$)
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 $1/\sigma^{\text{fid.}} d\sigma^{\text{fid.}}/d\phi^*_\eta$ within the fiducial lepton acceptance are presented in Table 2. At lower $\phi^*_\eta$ values the statistical and systematic uncertainties are of the same order, whilst for large $\phi^*_\eta$ values statistical uncertainties are dominating. The acceptance correction factors $A_\text{L}$ 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 $A_\text{L}$ is estimated from the extreme differences among predictions obtained with Resbos, MC@NLO, Sherpa, Alpgen, Hwhig and Powheg interfaced to Pythia8. Uncertainties in $A_\text{L}$ 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 $\phi^*_\eta$ in Fig. 2. The measurement is also compared to a QCD calculation by A. Banfi et al. [22] and to another obtained with Fwzv 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 $\mu_Q$, $\mu_R$ and $\mu_F$ between $m_Z/2$ and $2m_Z$, with the constraints $0.5 < \mu_i/\mu_j < 2$, where $i, j \in \{F, Q, R\}$, and $\mu_F/\mu_Q > 1$. Uncertainties coming from the PDFs are also considered [22]. For Fwzv, the CT10 PDF set is used. Uncertainties are evaluated by varying $\mu_R$ and $\mu_F$ by factors of two around the nominal scale $m_Z$ with the constraint $0.5 < \mu_R/\mu_F < 2$, by varying $\alpha_s$ 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 $\phi^*_\eta$ 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 Fwzv undershoots the data by $\sim 10\%$, as already observed for the $p_T^Z$ spectrum in Ref. [15]. At low $\phi^*_\eta$ 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 Fwzv is therefore only presented for $\phi^*_\eta > 0.1$. It is normalised using the total cross section predicted by Fwzv, which accurately describes experimental measurements [58].

The cross section is also measured double differentially in bins of $\phi^*_j$ for three independent bins of $|y_{Zj}|$ for both the $e^+e^-$ and $\mu^+\mu^-$ channels. The double differential cross-section measurements in the two channels are combined using the same $\chi^2$ minimisation procedure as used for the single differential cross section. The minimisation yields a total $\chi^2/\text{N}_{\text{dof}} = 118/102$. Measured values of the combined normalised differential cross section $1/\sigma^{\text{fid.}} d\sigma^{\text{fid.}}/d\phi^*_\eta$ within the fiducial lepton acceptance in all $\phi^*_j$ and $|y_{Zj}|$ 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 $\phi^*_\eta$ for the three $|y_{Zj}|$ ranges in Fig. 3. The measurement is also compared
Fig. 3. The ratio of the combined normalised differential cross section \( \sigma_{\text{fid}} \cdot d\sigma_{\text{fid}}/d\phi^*_\eta \) to the ResBos predictions as a function of \( \phi^*_\eta \) 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.

de 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 Pythia 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 \( \phi^*_\eta > 0.1 \). 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 Pythia is also able to describe the data to within \( 5\% \) over the whole \( \phi^*_\eta \) 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 \( \phi^*_\eta \) distribution of \( Z/\gamma^* \) boson candidates in \( \sqrt{s} = 7 \text{ TeV} \) 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 \( \phi^*_\eta \) 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 \( 66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV} \). The high number of \( Z/\gamma^* \) 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 \( \phi^*_\eta \) 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 \( \phi^*_\eta \) spectrum are provided by Sherpa and Powheg+Pythia8 Monte Carlo event generators. For \( \phi^*_\eta \) values above 0.1, predictions from Sherpa are able to reproduce the data to within \( \sim 2\% \). The low \( \phi^*_\eta \) part of the spectrum is, however, described less accurately than by ResBos. Double differential measurements as a function of \( \phi^*_\eta \) 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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