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 B S T R A C T**

A measurement of angular correlations in Drell–Yan lepton pairs via the \(\phi^*_\ell\) observable is presented. This variable probes the same physics as the \(Z/\gamma^*\) boson transverse momentum with a better experimental resolution. The \(Z/\gamma^* \rightarrow e^+e^-\) and \(Z/\gamma^* \rightarrow \mu^+\mu^-\) 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 \(\phi^*_\ell\) are measured separately for electron and muon decay channels. These channels are then combined for improved accuracy. The cross section is also measured differentially as a function of \(\phi^*_\ell\) 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 rescaled 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.
transverse momentum $p_T^Z$ [22]. Values of $\phi_4^m$ ranging from 0 to 1 probe the $p_T^Z$ distribution mainly up to $\sim 100$ GeV. The $\phi_4^m$ distribution of $Z/\gamma^*\to l^+l^-$ 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 $\phi_4^m$ 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 ($l=e,\mu$) transverse momentum $p_T^l > 20$ GeV, the lepton pseudorapidity $|\eta^l| < 2.4$ and the invariant mass of the lepton pair $66$ GeV < $m_{l\ell} < 116$ GeV. Correction factors allowing the extrapolation of the cross section from the fiducial lepton acceptance to the full lepton acceptance, restricted to $66$ GeV < $m_{l\ell} < 116$ GeV, are also presented. The reconstructed $\phi_4^m$ 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 $m_{l\ell}$ and $\phi_4^m$ are defined by the final-state leptons after QED FSR (“bare” leptons), or by recombining them with radiated photons within a cone of $d\Omega = (\Delta \eta)^2 + (\Delta \phi)^2 = 0.1$ (“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 $\alpha_s$, 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 $O(\alpha_s^2)$ are available for $Z/\gamma^*\to l^+l^-$ 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 $O(\alpha_s)$. This is corrected to $O(\alpha_s^2)$ 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 [42,46], 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 ($|\eta| < 0.7$), and 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 $Z/\gamma^*\to l^+l^-$ signal processes and to unfold the measured $\phi_4^m$ 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 $W \to ll\nu$ 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 overplaying 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
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-smearing 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 $\phi$ and 0.0012 for $\eta$. The highest and second highest $p_T$ electrons are required to have a transverse momentum $p_T^{e_1} > 25$ GeV and $p_T^{e_2} > 20$ GeV, respectively. The electron pseudorapidity must satisfy $|\eta| < 2.4$ with the calorimeter barrel/endcap transition region $1.37 < |\eta| < 1.52$ 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 $p_T^{\mu} > 18$ 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 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 $\phi$ and 0.0011 for $\eta$.

$Z/\gamma^{\ast} \rightarrow e^+e^-$ events are selected by requiring two oppositely charged same-flavour leptons with an invariant mass $m_{ee} < 116$ GeV. After these selection requirements 1.22 - 10$^9$ electron- and 1.69 - 10$^9$ dimuon candidate events are found in data. Background contributions from $Z/\gamma^{\ast} \rightarrow t\bar{t} \gamma$, $W \rightarrow e\nu$, $t\bar{t}$ and diboson production are estimated using MC simulations. The cross sections are normalised to next-to-next-to-leading-order (NNLO) predictions for $Z/\gamma^{\ast}$ and $W$ production using Feyn, 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 main background at high $\phi^*_h$ values arises from $tt$ and diboson production.

At low $\phi^*_h$ values the background is dominated by multi-jet production, where a jet is falsely identified as a primary $e$ or $\mu$. 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, $50 \text{ GeV} < m_{\ell\ell} < 150 \text{ GeV}$ (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 $\phi^*_h$ values. An irreducible background may also arise from the production of a lepton pair via photon-photon interactions, $\gamma\gamma \rightarrow \ell^+\ell^-$. This contribution was evaluated at leading order using FENZI 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 $\phi^*_h$ or of $\langle \phi^*_h \rangle_{\gamma\gamma}$ 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 $\phi^*_h$ bin which have generator-level $\phi^*_h$ in the same bin, is always more than 83% and reaches 98% in the highest $\phi^*_h$ 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 $\phi_\eta$ bins are listed below.

- Uncertainties in the estimation of the number of background events from multi-jet, $W \rightarrow \ell V$ 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 0.03% 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 $\phi_\eta$ 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 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.

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 $Z/\gamma \rightarrow e^+e^-$ 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 $\chi^2/\nu_{\text{dof}} = 33.2/34$, indicating a good consistency between the electron and muon data. Measured values of the combined normalised differential cross section $1/\sigma_{\text{fid}} \cdot d\sigma_{\text{fid}}/d\phi_{\mu}$ within the fiducial lepton acceptance are presented in Table 2. At lower $\phi_{\mu}$ values the statistical and systematic uncertainties are of the same order, whilst for large $\phi_{\mu}$ values statistical uncertainties are dominating. The acceptance correction factors $A_\mu$ 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 $p_T^\ell$ to ResBos predictions. The uncertainty in $A_\mu$ is estimated from the extreme differences among predictions obtained with ResBos, MCFM09, SHHERPA, ALPGEN, HERWIG and POWHEG interfaced to PyTHIA8. Uncertainties in $A_\mu$ 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 $\phi_{\mu}$ in Fig. 2. The measurement is also compared to a QCD calculation by A. Banfi et al. [22] and to another obtained with Fwz2.1. 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 renormalisation, resummation and factorisation scales $\mu_F, \mu_R$ and $\mu_T$ between $m_Z/2$ and $2m_Z$, with the constraints $0.5 < \mu_i/\mu_j \leq 2$, where $i, j \in \{F, Q, R\}$, and $\mu_T/\mu_Q \geq 1$. Uncertainties coming from the PDFs are also considered [22]. For Fwz2, the CT10 PDF set is used. Uncertainties are evaluated by varying $\mu_F$ and $\mu_R$ by factors of two around the nominal scale $m_Z$ with the constraint $0.5 < \mu_F/\mu_R \leq 2$, 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 $\phi_{\mu} < 0.1$, increasing to 5\% for higher $\phi_{\mu}$ values. This difference is smaller than the uncertainty in ResBos predictions due to the propagation of PDF eigenvector sets, which amounts to 4\% for $\phi_{\mu} < 0.1$ and 6\% above. The description of data provided by calculations from A. Banfi et al. [22] is less good than the ResBos theory, but observed differences remain within the theoretical uncertainties of the calculation. The prediction obtained with Fwz2 undershoots the data by $\sim 10\%$, as already observed for the $p_T^\ell$ spectrum in Ref. [15]. At low $\phi_{\mu}$ values, corresponding mainly to low $p_T^\ell$, fixed-order perturbative QCD calculations are not expected to give an adequate description of the cross section. The prediction from Fwz2 is therefore only presented for $\phi_{\mu} > 0.1$. It is normalised using the total cross section predicted by Fwz2, which accurately describes experimental measurements [58].

The cross section is also measured double differentially in bins of $\phi_{\mu}$ for three independent bins of $|y_{\ell}|$ 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 $\chi^2/\nu_{\text{dof}} = 118/102$. Measured values of the combined normalised differential cross section $1/\sigma_{\text{fid}} \cdot d\sigma_{\text{fid}}/d\phi_{\mu}$ within the fiducial lepton acceptance in all $\phi_{\mu}$ and $|y_{\ell}|$ 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 $\phi_{\mu}$ for the three $|y_{\ell}|$ ranges in Fig. 3. The measurement is also compared...
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 $\phi^*_0 > 0.1$. In particular, SHERPA describes the data better than ResBos over all $|y_Z|$ bins for $\phi^*_0 > 0.1$. However, for $\phi^*_0 < 0.1$ the deviations of SHERPA or ALPGEN from the data are ~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 $\phi^*_0$ 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 ~10% are observed. The MC@NLO generator interfaced to HERWIG does not properly describe the data for $\phi^*_0 > 0.1$, and deviations from data of the order of 4–7% are observed for $\phi^*_0 < 0.1$ depending on the $|y_Z|$ bin. The level of agreement between different MC generators and data is very similar for comparisons at the higher level.

8. Conclusion

A measurement of the $\phi^*_0$ distribution of $Z/\gamma^* \mu$ 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$^{-1}$. Normalized differential cross sections as a function of $\phi^*_0$ have been measured in bins of the Z boson rapidity $y_Z$ up to $|y_Z| < 3$ for electron and muon pairs with an invariant mass $66$ GeV < $m_{\ell\ell}$ < 116 GeV. The high number of $Z/\gamma^* \mu$ 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 $\phi^*_0 < 0.5$ increasing to 0.8% at larger $\phi^*_0$ values.

The cross-section measurements have been compared to re-scaled QCD predictions combined with fixed-order perturbative QCD calculations. Calculations using ResBos provide the best description 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 $\phi^*_0$ spectrum are provided by SHERPA and POWHEG+PYTHIA8 Monte Carlo event generators. For $\phi^*_0$ values above 0.1, predictions from SHERPA are able to reproduce the data to within ~2%. The low $\phi^*_0$ part of the spectrum is, however, described less accurately than by ResBos. Double differential measurements as a function of $\phi^*_0$ 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.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and PWF, Austria; ANAS, Azerbaijan; STFC, Belgium; CNPq and FAPERJ, Brazil; NSERC, NRC and CFI, Canada; CERN, CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSM CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DS/JRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

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

Open access

This article is published Open Access at scienceDirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, reproduction in any medium, provided the original authors and source are credited.

References


Atlas Collaboration

D. Vladoiu 98, M. Vlasak 126, A. Vogel 21, P. Vokac 126, G. Volpi 47, M. Volpi 86, G. Volpini 89a
R. Voss 30, J.H. Vossebeld 73, N. Vranjes 136, M. Vranjes Milosavljevic 105, V. Vrba 125, M. Vreeswijk 105,
T. Vu Anh 48, R. Vuillermet 30, I. Vukotic 31, W. Wagner 175, P. Wagner 21, H. Wahlen 175, S. Wahrmann 44,
J. Wakabayashi 101, S. Walch 75, J. Walder 71, R. Walker 98, W. Walkowiak 141, R. Wall 176, P. Waller 73,
T. Wang 21, A. Warburton 85, C.P. Ward 28, D.R. Wardrope 77, M.Warsinski 48, A. Washbrook 46,
C. Wasicik 52, I. Watanabe 66, P.M. Watkins 18, A.T. Watson 18, I.J. Watson 150, M.F. Watson 18, G. Watts 138,
S. Watts 82, A.T. Waugh 150, B.M. Waugh 77, M.S. Weber 17, J.S. Webster 31, A.R. Weidberg 118, P. Weigell 99,
J. Weingarten 54, C. Weiser 48, P.S. Wells 30, T. Wenaus 25, D. Wendland 16, Z. Weng 151, T. Wengler 30,
S. Wenig 30, N. Werms 21, M. Werner 48, P. Werner 30, M. Werth 163, M. Wessels 58a, J. Wetter 161,
C. Weydert 55, K. Whalen 26, A. White 8, M.J. White 86, S. White 122a,122b, S.R. Whitehead 118,
D. Whiteson 163, D. Whittington 60, D. Wicke 175, F.J. Wickens 129, W. Wiedemann 173, M. Wielers 129,
P. Wienenman 21, C. Wiglesworth 75, L.A.M. Wiik-Fuchs 21, P.A. Wijeratne 77, A. Wildauer 99,
M.A. Wildt 42a, I. Wilhelm 127, H.G. Wilkins 30, J.Z. Will 98, E. Williams 35, H.H. Williams 120,
S. Williams 28, W. Willis 35, S. Willocq 84, J.A. Wilson 18, M.G. Wilson 143, A. Wilson 87, I. Wingert-Seee 5,
S. Winkelmann 48, F. Winklmeier 38, M. Wittgen 143, S.J. Wollstadt 81, M.W. Wolter 39, H. Wolters 124a,i,
W.C. Wong 41, G. Woodeen 87, B.K. Wosiek 39, J. Wotschack 30, M.J. Woudstra 92, K.W. Wozniak 39,
K. Wright 53, M. Wright 53, B. Wrona 73, S.L. Wu 173, X. Wu 49, Y. Wu 33b,175, E. Wulf 35, B.M. Wynne 46,
S. Xella 36, M. Xiao 136, S. Xie 48, C. Xu 33b,2, D. Xu 33a, L. Xu 33b, B. Yabsley 150, S. Yacoob 145a,an
M. Yamada 65, H. Yamaguchi 155, A. Yamamoto 55, K. Yamamoto 63, S. Yamamoto 155, T. Yamamura 155,
T. Yamana 155, K. Yamauchi 101, T. Yamazaki 155, Y. Yamazaki 96, Z. Yan 22, H. Yang 33c, H. Yang 173,
J.K. Yang 82, Y. Yang 109, Z. Yang 46a,46b, S. Yanush 91, L. Yao 33a, Y. Yasu 65, E. Yatsenko 42, J. Ye 40,
S. Ye 25, A.L. Yen 57, M. Yilmaz 4c, R. Yosooefiyma 123, K. Yorita 171, R. Yoshida 6, K. Yoshihara 155,
M. Zeman 126, A. Zemla 39, O. Zenin 128, T. Ženiš 144a, Z. Zinonos 122a,122b, D. Zerwas 115,
Z. Zhao 33b, A. Zhemchugov 64, J. Zhong 118, B. Zhou 87, N. Zhou 163, Y. Zhou 151, C.G. Zhu 33d, H. Zhu 42,
J. Zhu 87, Y. Zhu 33b, X. Zhuang 98, V. Zhuravlov 99, A. Zibell 98, D. Zieminska 60, N.I. Zimin 64,
V.V. Zmouchko 128a, G. Zobenni 173, A. Zoccoli 20a,20b, M. zur Nedden 16, V. Zutshi 106, L. Zwalinski 30

1 School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 a) Department of Physics, Ankara University, Ankara; b) Department of Physics, Dumlupinar University, Kayseri; c) Department of Physics, Gazi University, Ankara; d) Division of Physics, TOBB University of Economics and Technology, Ankara; e) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPI-CNRS/ENSFP et Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 Department of Physics, University of Arizona, Tucson, AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Adriabrin Academy of Sciences, Baku, Azerbaijan
12 Instituto de Física de Altas Energías and Departamento de Física de la Universidad Autónoma de Barcelona and ICREA, Barcelona, Spain
13 a) Institute of Physics, University of Belgrade, Belgrade; b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 a) Department of Physics, Bogazici University, Istanbul; b) Division of Physics, Dogus University, Istanbul; c) Department of Physics Engineering, Gaziantep University, Gaziantep; d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
20 a) John Scienza di Bologna; b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, Universität Bonn, Bonn, Germany
23 Department of Physics, Boston University, Boston, MA, United States
24 a) Universidade Federal do Rio de Janeiro COPPE/EE, Rio de Janeiro; b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; c) Federal University of Sao Joao del Rei (UFJS), Sao Joao del Rei; d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 a) National Institute of Physics and Nuclear Engineering, Bucharest; b) University Politehnica Bucharest, Bucharest; c) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina