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Measurement of the transverse momentum distribution of Z/γ^* bosons in proton–proton collisions at $\sqrt{s}=7$ TeV with the ATLAS detector ☆

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ABSTRACT

A measurement of the Z/γ^* transverse momentum (p_T^Z) distribution in proton–proton collisions at $\sqrt{s}=7$ TeV is presented using $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ decays collected with the ATLAS detector in data sets with integrated luminosities of 35 pb^{-1} and 40 pb^{-1}, respectively. The normalized differential cross sections are measured separately for electron and muon decay channels as well as for their combination up to p_T^Z of 350 GeV for invariant dilepton masses 66 GeV $< m_{\ell\ell} <$ 116 GeV. The measurement is compared to predictions of perturbative QCD and various event generators. The prediction of resummed QCD combined with fixed order perturbative QCD is found to be in good agreement with the data.

1. Introduction

In hadron collisions, the weak vector bosons W and Z are produced with a momentum component transverse to the beam axis, which is balanced by a recoiling hadronic system mainly arising from initial state QCD radiation of quarks and gluons. The measurement of the boson transverse momentum offers a very sensitive way of studying dynamical effects of the strong interaction, complementary to measurements of the associated production of the bosons with jets [1]. The simple signatures of $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ production, which can be identified with little background, enable a precise measurement of the boson transverse momentum (p_T^Z) and thus provide an ideal testing ground for predictions of QCD and phenomenological models. Moreover, the knowledge of the p_T^Z distribution is crucial to improve the modelling of W boson production needed for a precise measurement of the W mass [2,3], in particular in the low p_T^Z region which dominates the cross section.

This Letter presents a measurement of the Z/γ^* normalized transverse momentum distribution in proton–proton collisions at $\sqrt{s}=7$ TeV using $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ decays collected in 2010 with the ATLAS detector in data sets with integrated luminosities of 35 pb^{-1} and 40 pb^{-1}, respectively. In the normalized transverse momentum distribution, many systematic uncertainties cancel. In particular, the precision of the measurement is not impaired by the uncertainty on the integrated luminosity. The normalized transverse momentum distribution is defined in the following way: $1/\sigma^{\text{fid}} \times d\sigma^{\text{fid}}/dp_T^Z$, where σ^{fid} is the measured inclusive cross section of $pp \to Z/\gamma^* + X$ multiplied by the branching ratio of $Z/\gamma^* \to \ell^+\ell^-$ within the fiducial acceptance, and X denotes the underlying event and the recoil system. For both the ee and $\mu\mu$ channels, the fiducial acceptance is defined by the lepton transverse momentum and pseudorapidity,[1] and by the invariant mass of the lepton pair $m_{\ell\ell}$: $p_T^\ell > 20$ GeV, $|\eta^\ell| < 2.4$ and 66 GeV $< m_{\ell\ell} <$ 116 GeV. The measurements in both decay channels are corrected for detector effects and QED final state radiation (FSR). The combined result is compared to predictions of perturbative QCD calculations and QCD-inspired models implemented in various event generators.

Predictions and previous measurements are discussed in Section 2. The ATLAS detector and trigger are described in Section 3. In Sections 4 and 5 the event simulation and selections are described. Section 6 reports the p_T^Z measurements for different treatments of QED final state radiation. Systematic uncertainties are discussed in Section 7. Section 8 presents the combined result which is compared with various models.

[1] The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive x-axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y-axis pointing upwards. The azimuthal angle φ is measured around the beam axis and the polar angle θ is the angle from the z-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

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2. QCD predictions and previous measurements

Perturbative QCD (pQCD) calculations have been performed up to $\mathcal{O}(\alpha_S^2)$ in the strong coupling constant α_S [4,5] and are expected to be reliable at large p_T^Z. In this kinematic regime, the cross section is dominated by the radiation of a single parton. Fully differential inclusive boson production cross sections can be obtained at $\mathcal{O}(\alpha_S^2)$ with Fewz [6,7] and Dynnlo [8]. While the integrated $\mathcal{O}(\alpha_S^2)$ cross section predictions are finite, the fixed order pQCD prediction diverges at vanishing p_T^Z. In this regime, the leading contribution of multiple soft gluon emissions to the inclusive cross section can be resummed to all orders [9–11] up to next-to-next-to-leading logarithms (NNLL) [12] in α_S. The Resbos generator [13] matches the prediction of soft gluon resummation including a non-perturbative form factor [14] at low p_T^Z with the fixed order pQCD calculation at $\mathcal{O}(\alpha_S)$ at high p_T^Z, which is corrected to $\mathcal{O}(\alpha_S^2)$ using K-factors.

Similar to resummed calculations, parton showers provide an all-order approximation of parton radiation in the soft and collinear region. In order to describe the large p_T^Z region, the parton shower based leading-order event generators Pythia [15] and Herwig [16] apply weights to the first or hardest branching, respectively, to effectively merge the $\mathcal{O}(\alpha_S^0)$ and $\mathcal{O}(\alpha_S)$ pQCD predictions. The next-to-leading order (NLO) Monte Carlo generators Mc@nlo [17] and Powheg [18] incorporate NLO QCD matrix elements consistently into the parton shower frameworks of Herwig or Pythia.

The Alpgen [19] and Sherpa [20] event generators implement tree-level matrix elements for the generation of multiple hard partons in association with the weak boson. The matrix-element calculations for various parton multiplicities are matched with parton showers (which in the case of Alpgen are provided by either Pythia or Herwig) such that double counting is explicitly avoided by means of weighting procedures [21] or veto algorithms [19].

As the predictions of these generators differ significantly and show a considerable dependence on adjustable internal parameters [22], a precise measurement of the boson transverse momentum distribution is an important input to validate and tune these models.

The Z/γ^* boson p_T distribution has been measured in proton–antiproton collisions at the Tevatron collider at centre of mass energies of $\sqrt{s} = 1.8$ TeV and 1.96 TeV [23–27]. For $p_T^Z \lesssim 30$ GeV, these measurements found a good agreement with Resbos and disfavoured models [28] suggesting a broadening of the p_T^Z distribution for small x values [25,27], where x is the fraction of the momentum of one of the two partons with respect to the proton momentum. At large p_T^Z, the $\mathcal{O}(\alpha_S^2)$ pQCD prediction was reported to underestimate the measured cross section by up to about 25% [25,26].

3. The ATLAS detector

The ATLAS detector system [29] comprises an inner tracking detector immersed in a 2 T axial magnetic field, a calorimeter, and a large muon spectrometer with a superconducting toroid magnet system. Charged particle tracks and vertices are reconstructed with silicon pixel and strip detectors covering $|\eta| < 2.5$ and transition radiation detectors covering $|\eta| < 2.0$. These tracking detectors are surrounded by a finely segmented calorimeter system which provides three-dimensional reconstruction of particle showers up to $|\eta| < 4.9$. The electromagnetic compartment uses liquid argon as the active material and is divided into barrel ($|\eta| < 1.5$), end-cap ($1.4 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) components. The hadron calorimeter is based on scintillating tiles in the central region ($|\eta| < 1.7$). It is extended up to 4.9 in pseudorapidity by end-caps and forward calorimeters which use liquid argon. The muon spectrometer is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, covering a range of $|\eta| < 2.7$ and providing an integral magnetic field varying from about 1 to 8 Tm. Three stations of drift tubes and cathode strip chambers enable precise muon track measurements, and resistive-plate and thin-gap chambers provide muon triggering capability and additional measurements of the φ coordinate.

The ATLAS detector has a three-level trigger system which reduces the event rate to approximately 200 Hz before data transfer to mass storage. The triggers employed require the presence of a single electron or muon candidate with $p_T > 15$ GeV or $p_T > 13$ GeV, respectively. Lower thresholds were used for the early data. The trigger efficiencies are defined for $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ events as the fraction of triggered electrons or muons with respect to the reconstructed lepton and are studied as a function of their p_T and η. For muons, the efficiencies are also obtained separately in φ regions which match the geometry of the trigger chambers. The efficiency for single leptons is derived from data using $Z/\gamma^* \to \ell^+\ell^-$ candidate events or using independent triggers by matching reconstructed lepton candidates to trigger signals in the calorimeter (muon spectrometer) in case of the ee ($\mu\mu$) decay channel. For $p_T^\ell > 20$ GeV, the efficiency is 99% for electrons and 77% (93%) for muons in the barrel (end-cap). For signatures with two high-E_T electrons, the trigger is fully efficient. The trigger efficiency for $Z/\gamma^* \to \mu^+\mu^-$ events is determined to be on average 97.7% and to be constant as a function of p_T^Z within an uncertainty of 0.1–0.7% depending on p_T^Z.

4. Event simulation

The properties, including signal efficiencies and acceptances, of $Z/\gamma^* \to e^+e^-$, $Z/\gamma^* \to \mu^+\mu^-$ and background processes are modelled with Pythia [15] using the MRST2007LO* [30] parton distribution functions (PDF), Mc@nlo [17] and Powheg using CTEQ6.6 [31] PDFs. Mc@nlo uses Herwig for the parton shower and Jimmy [32] for the underlying event. Powheg is interfaced to Pythia for the underlying event and the parton shower. The event generators are interfaced to Photos [33] to simulate QED FSR. Version 6.4 of Pythia is used with the p_T-ordered parton shower and with parameters describing the properties of the underlying event which were tuned to Tevatron measurements [34]. For systematic studies and comparisons, a Mc@nlo based signal sample is used with underlying event parameters (Jimmy) tuned to Tevatron and 7 TeV ATLAS pp collision data [35]. The response of the ATLAS detector to the generated particles is modelled using Geant4 [36], and the fully simulated events [37] are passed through the same reconstruction chain as the data. The Monte Carlo simulation (MC) is corrected for differences with respect to the data in the lepton reconstruction and identification efficiencies as well as in energy (momentum) scale and resolution. The efficiencies are determined from a tag-and-probe method based on reconstructed Z and W events [38,39], while the resolution and scale corrections are obtained from a fit to the observed Z boson line shape. The lepton identification efficiencies can depend on the hadronic activity, which is correlated with the Z/γ^* transverse momentum. Therefore, using the tag-and-probe method, it is verified that the p_T^Z dependence of the single lepton efficiency is correctly modelled after efficiency corrections. Differences between data and simulation are mostly consistent with statistical fluctuations and are considered as systematic uncertainties due to the modelling of the efficiencies as described in Section 7.

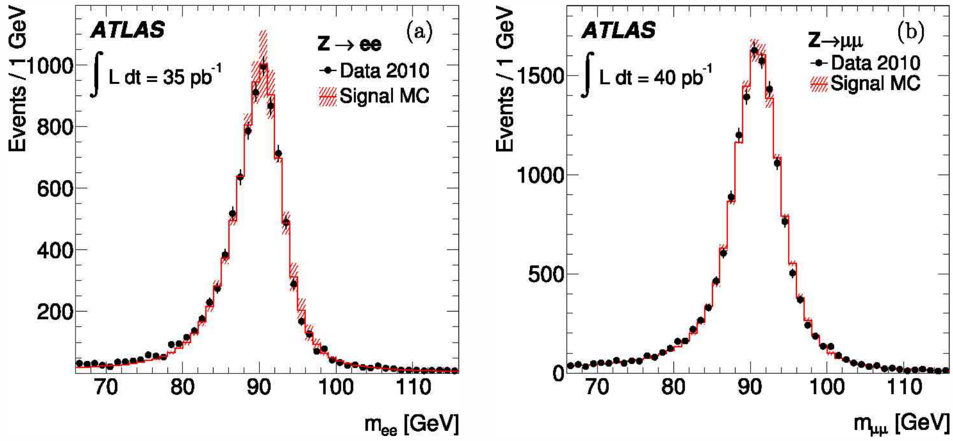

Fig. 1. The observed (a) dielectron and (b) dimuon invariant mass distributions compared to simulation. The shaded bands indicate the systematic uncertainty on the MC prediction due to the lepton momentum resolution correction. The Pythia sample, which is normalized to the next-to-next-to-leading order (NNLO) prediction [40,6,7], is used for signal events. The total background, which is invisible on this scale, amounts to only 1.5% and 0.4% in the ee and $\mu\mu$ decay channels, respectively.

Multiple pp interactions per bunch crossing (*pileup*) are accounted for by overlaying simulated minimum bias events. To match the observed instantaneous luminosity profile, the MC events are reweighted to yield the same distribution of the number of primary vertices as measured in the data.

In the following, if not stated otherwise, the generated samples are fully simulated, pileup and resolution corrected, and interfaced to Photos, with Pythia as the default MC signal sample. The background samples are produced with Pythia for $W \to \ell\nu$, with Mc@nlo and Powheg for $t\bar{t}$, and with Pythia and Mc@nlo for $Z/\gamma^* \to \tau^+\tau^-$.

5. Event selection

The analysis uses data taken during stable beam conditions with properly operating inner detector, magnets, and calorimeter or muon spectrometer, in case of the ee or $\mu\mu$ channel, respectively. Events are required to have at least one primary vertex reconstructed from at least three tracks. Z/γ^* events are selected by requiring two oppositely charged electrons or muons, defined below, with an invariant mass 66 GeV $< m_{\ell\ell} <$ 116 GeV.

Electrons are reconstructed from the energy deposits in the calorimeter matched to inner detector tracks. They are required to have a transverse energy $E_T^e > 20$ GeV and pseudorapidity $|\eta^e| < 2.4$, excluding the transition regions between the barrel and end-cap calorimeter components at $1.37 < |\eta^e| < 1.52$. They should pass *medium* identification criteria based on shower shape and track quality variables [38] to provide rejection against hadrons. The single electron selection efficiency varies in the range 90–96% depending on pseudorapidity and azimuthal angle.

Muons are reconstructed from matching tracks in the inner detector and muon spectrometer with $p_T^\mu > 20$ GeV and $|\eta^\mu| < 2.4$ measured using the information from these two detector subcomponents. To ensure the compatibility of the muon track with the primary vertex, the corresponding impact parameters in the transverse and longitudinal direction with respect to the beam axis have to be smaller than 1 mm and 5 mm, respectively. The muon candidates are required to be isolated to suppress background from heavy flavour production using the transverse momentum sum of tracks with $p_T > 1$ GeV within a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.2$ around the muon track. This sum has to be smaller than $0.2 \times p_T^\mu$. The single muon selection efficiency is of the order of 87–95% depending on pseudorapidity and azimuthal angle.

After this selection, 8923 $Z/\gamma^* \to e^+e^-$ and 15 060 $Z/\gamma^* \to \mu^+\mu^-$ candidate events are found in the data. The main reasons for the difference in the number of candidate events in the ee and $\mu\mu$ decay channels are: the integrated luminosity for which all relevant detector components were operating properly; regions in the electromagnetic calorimeter with readout problems; a reduced acceptance for electrons in the transition region between the barrel and end-cap calorimeter. Fig. 1 demonstrates the agreement of the data and the simulation in the dilepton mass spectrum for the selected events including the background, after applying the corrections described in Section 4.

The background contribution from $Z/\gamma^* \to \tau^+\tau^-$, W boson, and $t\bar{t}$ production is estimated as a function of p_T^Z using simulation, where the cross sections are normalized to next-to-next-to-leading order (NNLO) predictions for Z/γ^* and W and NLL–NLO predictions for $t\bar{t}$ production. The procedure outlined in Ref. [38] is followed here.

For both ee and $\mu\mu$ channels, the main background at high p_T^Z arises from $t\bar{t}$ production. At low p_T^Z the background is dominated by QCD multijet production, where a jet is falsely identified as a primary e or μ. Its contribution is determined from the data as follows.

In the ee channel, the normalization of the multijet contribution is derived from a fit of signal and background templates to the observed dilepton invariant mass distribution with loosened identification requirements for one of the two reconstructed electron candidates. An extended mass range of 50 GeV $< m_{ee} <$ 130 GeV is used which provides a better background constraint in the off-resonance region. The normalization derived from this loosened selection has to be scaled to the Z/γ^* event selection, which requires two reconstructed electron candidates of medium quality. The scaling factor is determined from a QCD multijet enhanced control sample with single electron candidates which fulfil the loosened electron identification requirements. The contamination with other events, in particular the contribution from W production, is suppressed by rejecting events with large missing transverse energy. The remaining contamination is determined using simulated events. The systematic uncertainty of the normalization is determined by varying the background templates and the criteria for the loosened selection. The shape of the multijet background as a function of p_T^Z is determined from a dielectron sample with an invariant mass 66 GeV $< m_{ee} <$ 116 GeV for which exactly one electron passes and one fails the medium identification criteria. The difference between same and opposite sign events is taken as the shape uncertainty.

Table 1
The measured normalized differential cross section $1/\sigma^{\text{fid}}\,\text{d}\sigma^{\text{fid}}/\text{d}p_{\text{T}}^{Z}$ in bins of p_{T}^{Z} for $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ production. The cross sections, which are to be multiplied by the factor k, are reported with respect to three different treatments of QED final state radiation for the definition of lepton and Z/γ^* momentum at particle level: corresponding to the Z/γ^* propagator (propag.), to dressed leptons (with recombined radiated photons within a cone of $\Delta R = 0.1$), and to bare leptons, respectively. The relative statistical (stat.) and total systematic (syst.) uncertainties are given. The data can be obtained electronically through the HepData repository [43].

p_{T}^{Z} bin (GeV)	$1/\sigma^{\text{fid}}\,\text{d}\sigma^{\text{fid}}/\text{d}p_{\text{T}}^{Z}$ (GeV^{-1}) $Z/\gamma^* \to e^+e^-$				uncert. (%)		$Z/\gamma^* \to \mu^+\mu^-$				uncert. (%)	
	propag.	dressed	bare	k	stat.	syst.	propag.	dressed	bare	k	stat.	syst.
0–3	3.48	3.40	3.21	$\times 10^{-2}$	3.3	4.7	3.75	3.66	3.58	$\times 10^{-2}$	2.6	5.0
3–6	5.85	5.78	5.60	$\times 10^{-2}$	2.4	3.3	5.81	5.74	5.68	$\times 10^{-2}$	2.0	4.0
6–9	4.61	4.62	4.64	$\times 10^{-2}$	2.7	2.3	4.67	4.68	4.69	$\times 10^{-2}$	2.1	1.6
9–12	3.43	3.46	3.56	$\times 10^{-2}$	3.1	2.4	3.50	3.54	3.58	$\times 10^{-2}$	2.4	1.6
12–15	2.93	2.97	3.09	$\times 10^{-2}$	3.3	2.7	2.67	2.72	2.76	$\times 10^{-2}$	2.8	1.7
15–18	2.04	2.08	2.16	$\times 10^{-2}$	3.9	3.0	2.13	2.17	2.20	$\times 10^{-2}$	3.1	1.7
18–21	1.64	1.67	1.73	$\times 10^{-2}$	4.4	3.3	1.69	1.72	1.74	$\times 10^{-2}$	3.5	1.8
21–24	1.32	1.33	1.37	$\times 10^{-2}$	4.8	3.6	1.35	1.36	1.37	$\times 10^{-2}$	4.0	1.8
24–27	1.08	1.08	1.11	$\times 10^{-2}$	5.5	3.8	1.15	1.16	1.17	$\times 10^{-2}$	4.3	1.9
27–30	1.02	1.03	1.03	$\times 10^{-2}$	6.5	4.0	0.87	0.88	0.88	$\times 10^{-2}$	5.0	2.0
30–36	7.22	7.24	7.26	$\times 10^{-3}$	4.8	4.2	6.45	6.46	6.45	$\times 10^{-3}$	4.1	2.1
36–42	4.89	4.88	4.85	$\times 10^{-3}$	5.8	4.5	4.63	4.63	4.62	$\times 10^{-3}$	4.9	2.2
42–48	3.66	3.64	3.59	$\times 10^{-3}$	7.0	4.8	3.97	3.95	3.94	$\times 10^{-3}$	5.3	2.4
48–54	3.26	3.25	3.20	$\times 10^{-3}$	7.8	5.0	2.90	2.88	2.86	$\times 10^{-3}$	6.2	2.6
54–60	2.14	2.13	2.08	$\times 10^{-3}$	9.2	5.4	2.14	2.13	2.11	$\times 10^{-3}$	7.2	2.7
60–80	1.21	1.20	1.17	$\times 10^{-3}$	6.5	5.7	1.31	1.30	1.28	$\times 10^{-3}$	5.1	3.0
80–100	5.69	5.63	5.44	$\times 10^{-4}$	9.8	5.9	5.52	5.47	5.40	$\times 10^{-4}$	7.8	3.5
100–180	1.74	1.73	1.67	$\times 10^{-4}$	9.6	6.1	1.52	1.51	1.49	$\times 10^{-4}$	7.5	4.4
180–350	0.78	0.77	0.73	$\times 10^{-5}$	27.0	7.8	1.14	1.14	1.11	$\times 10^{-5}$	18.9	6.6

For the $\mu\mu$ selection, the multijet contribution is estimated from four two-dimensional regions which are obtained by changing the mass window to 40 GeV $< m_{\mu\mu} <$ 60 GeV or by inverting the isolation criterion. The normalization is determined from the number of candidate events in these four regions which is corrected by the expected number of non-QCD multijet background events and number of signal events. The number of signal events is determined from the measurement in the signal region which is corrected for the background including the multijet background, and extrapolated to the other regions using relative efficiencies extracted from the simulation. The resulting equation can be solved for the number of QCD multijet background events. The shape is determined from the control region where both muon candidates are non-isolated and their invariant mass is within 66 GeV $< m_{\mu\mu} <$ 116 GeV. Systematic uncertainties are determined by comparing the results to those of alternative methods which use template fits or same sign and opposite sign events.

The total background contribution, which amounts to $(1.5 \pm 0.6)\%$ and $(0.4 \pm 0.2)\%$ in the ee and $\mu\mu$ channels, respectively, is found to increase from 0.5% (0.2%) to 3.5% (1.5%) as a function of p_{T}^{Z} in the ee ($\mu\mu$) analysis.

6. The measured p_{T}^{Z} distribution

The Z/γ^* transverse momentum is reconstructed from the measured lepton momenta. The p_{T}^{Z} range is divided into 19 bins from 0 GeV to 350 GeV with widths of 3 GeV for $p_{\text{T}}^{Z} < 30$ GeV and increasing widths at larger transverse momenta as given in Table 1. For this binning, the fraction of simulated events reconstructed in a particular p_{T}^{Z} bin which have generator-level p_{T}^{Z} in the same bin is always better than 60% and reaches values above 90% in the highest p_{T}^{Z} bins for both decay channels. The bin-by-bin efficiency, defined as the ratio between the number of signal events which pass the final selection and the total number of generated events within the fiducial region, are on average about 56% in the ee and 83% in the $\mu\mu$ channel, respectively. Three Z/γ^* candidate events with $p_{\text{T}}^{Z} > 350$ GeV are found, which are not considered further due to the limited statistical significance.

The observed p_{T}^{Z} spectrum is found to be well described by the simulation, using the default MC signal samples and background estimations as described in Sections 4 and 5. A bin-by-bin efficiency correction is used to correct (unfold) the observed data for detector effects and QED FSR, where the correction factors are determined from the default MC signal sample. Alternative matrix unfolding methods [41,42], which explicitly take the bin-to-bin migration into account, yield compatible results. However, these techniques require higher data statistics to fully exploit their advantages. Therefore they are currently used only to estimate the systematic uncertainties due to the unfolding method as discussed in Section 7.

In Table 1, the cross section measurements in the ee and $\mu\mu$ decay channels are reported in the fiducial volume, which is defined by the lepton acceptance $p_{\text{T}}^{\ell} > 20$ GeV and $|\eta^{\ell}| < 2.4$, and the invariant mass of the lepton pair 66 GeV $< m_{\ell\ell} <$ 116 GeV. This implies for the ee decay channel a small acceptance correction due to the discarded events, in which one or more electrons are within the calorimeter transition region, $1.37 < |\eta^{e}| < 1.52$. The resulting correction of the normalized differential cross section is smaller than 0.6%. The measurement is reported with respect to three distinct reference points at particle level regarding QED FSR corrections. The true dilepton mass $m_{\ell\ell}$ and transverse momentum p_{T}^{Z} are either defined by the final state leptons after QED FSR ("bare" leptons), or by recombining them with radiated photons within a cone of $\Delta R = 0.1$ ("dressed" leptons), or by the Z/γ^* propagator. The propagator definition corresponds to a full correction for QED FSR effects, allows for a combination of the electron and muon channels, and facilitates a direct comparison of the measurement with QCD calculations. The QED FSR corrections are at most 8% (5%) for the normalized differential cross section in the ee ($\mu\mu$) decay channel.

7. Systematic uncertainties

Systematic uncertainties arise mainly from lepton efficiencies, momentum scale and resolution, and from the unfolding procedure. They are evaluated by varying separately each parameter in question and recalculating the bin-by-bin correction factors used to unfold the p_T^Z spectrum. The observed deviation in the unfolded distributions is limited by the statistics of the simulated events. The statistical component of these deviations is estimated using a bootstrap method [44] based on multiple resampling of the simulated events. Each sample has the same size and may contain the same events multiple times. Symmetric systematic uncertainties are derived in such a way [45] that the area spanned by these uncertainties covers 68% of the integral over a Gaussian with mean and width equal to the mean and standard deviation of the bootstrap distributions. The resulting uncertainties are equal to the standard deviation if the bootstrap distribution is centred at zero, and approach the mean plus half the standard deviation if the mean deviates from zero.

The following sources of systematic uncertainties on the measured normalized differential cross section are evaluated, where the quoted uncertainties are relative percentages.

Lepton reconstruction and identification: The efficiencies are determined as a function of p_T^Z using a tag-and-probe method. Due to the limited statistics at high p_T^Z, the uncertainties are parametrized by a function which increases with p_T^Z. For the *ee* analysis, the uncertainty due to the electron reconstruction and identification varies between 1.0% and 3.2%. An additional uncertainty of 0.1% arises from the modelling of local calorimeter readout problems. In the case of the $\mu\mu$ selection, the uncertainties due to the efficiencies on the trigger, on the muon reconstruction and identification, and on the isolation requirement are evaluated separately and are found to be within 0.4%, 2.3%, and 1.0%, respectively, except for the three highest p_T^Z bins, where they reach 0.8%, 4.9%, and 2.7%.

Lepton energy (momentum) scale and resolution: The scale and resolution corrections of the simulation are varied within their uncertainties estimated from the fit to the observed Z/γ^* line shape. Correlations across p_T^Z bins are taken into account. Due to the normalization to the inclusive cross section, a systematic shift at low p_T^Z is balanced by a shift in the opposite direction at high p_T^Z. In the *ee* ($\mu\mu$) analysis, the uncertainty due to scale variations is found to be 2.7% (0.2%) for the lowest bin, decreasing down to 0.2% ($< 0.1\%$) at $p_T^Z \sim 10$ GeV, and then increasing up to 4.4% (0.4%) at the highest p_T^Z values. Uncertainties due to resolution are estimated to be 0.5% for the *ee* channel and between 0.1% and 0.7% for the $\mu\mu$ channel.

Unfolding procedure: The bin-by-bin correction factors depend on the shape of the assumed underlying p_T^Z distribution, which leads to a systematic uncertainty evaluated in the following way. The default MC signal sample (Pythia) is reweighted to different true p_T^Z shapes using Resbos and Mc@nlo. The variance of these generator predictions does not entirely cover the observed difference between simulation and data. Therefore the Pythia signal sample is reweighted, in addition, to distributions based on unfolded data. The spectra obtained by unfolding the data either with the bin-by-bin method or alternative matrix unfolding techniques [41,42] are considered. These new corrected spectra feature different uncertainties. The bin-by-bin method suffers a larger systematic uncertainty due to the assumed true p_T^Z shape, whereas matrix-based unfolding is nearly independent of this assumption, but suffers from a larger statistical uncertainty. Each of the reweighted spectra is treated in the same way as the data, and is unfolded with the default bin-by-bin correction factors. The maximum deviation from the respective true p_T^Z spectrum is considered as a systematic uncertainty. A possible influence from the parton shower and hadronization model is estimated by comparing the bin-by-bin correction factors determined from either the default Pythia sample or the Mc@nlo sample. Mc@nlo uses Herwig for the parton shower and Jimmy for the underlying event. To separate these model uncertainties from the uncertainty due to the underlying p_T^Z distribution, which is already accounted for, the Mc@nlo sample is reweighted to the p_T^Z shape of the default MC signal sample. The uncertainties due to the shape of the p_T^Z distribution and due to the modelling of the parton shower and the hadronization are combined to yield the total unfolding uncertainty, which is found to be within 2.0% (1.3%) in the *ee* ($\mu\mu$) channel for p_T^Z between 6 GeV and 100 GeV. For $p_T^Z < 6$ GeV the uncertainty is as large as 3.6% (4.7%) and for $p_T^Z > 100$ GeV it is as large as 4.2% (2.9%) in the *ee* ($\mu\mu$) channel. The unfolding uncertainty is dominated by the deviations observed when reweighting the default MC signal sample to the p_T^Z distributions obtained from the data with the matrix unfolding techniques.

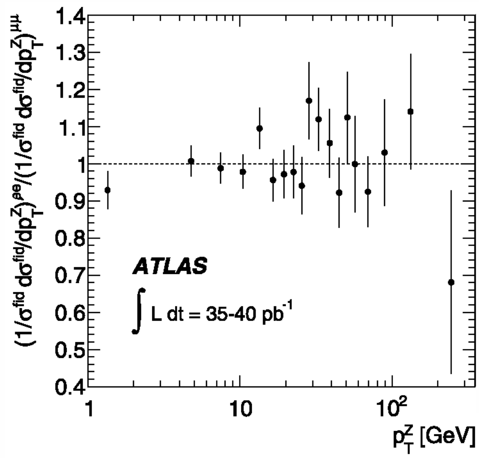

Fig. 2. Ratio of the normalized differential cross section for $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ production as a function of p_T^Z at Z/γ^* propagator level using an integrated luminosity of 35 pb^{-1} and 40 pb^{-1}, respectively. The error bars shown include statistical and systematic uncertainties. The systematic uncertainties due to the unfolding procedure and QED FSR, which are correlated between the electron and muon decay channel, are omitted.

Background contamination: Uncertainties in the estimation of the background from QCD multijet, weak boson, and $t\bar{t}$ production yield values of up to 1.4% (0.6%) for the *ee* ($\mu\mu$) analysis when propagated to the normalized differential cross section.

Modelling of pileup corrections: Pileup has a small influence on this measurement. An uncertainty of 0.3% on the normalized differential cross section is derived.

MC sample statistics: The uncertainties are within 0.4%–1.5% (0.3%–0.8%) in the *ee* ($\mu\mu$) channel, except for highest p_T^Z values for which the uncertainties reach 3.6% (1.6%).

QED final state radiation: A conservative systematic uncertainty of 0.6% due to the p_T^Z-dependent modelling of QED FSR is assigned. This uncertainty addresses both potential differences between the approximation used in Photos compared to exact second order QED FSR matrix element calculations [46,47] and uncertainties in the simulation of the interaction of the radiated photons with the detector material [38].

The systematic uncertainties listed above are added quadratically to obtain the total systematic uncertainties listed in Table 1.

8. Results and conclusions

The normalized differential cross section measurements for $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ production are in good agreement with each other at the Z/γ^* propagator level; see Fig. 2 for the ratio of the measured cross sections. The two decay channels are combined at Z/γ^* propagator level using a χ^2 minimization method which takes into account the correlated systematic uncertainties for the *ee* and $\mu\mu$ channels [48]. The uncertain-

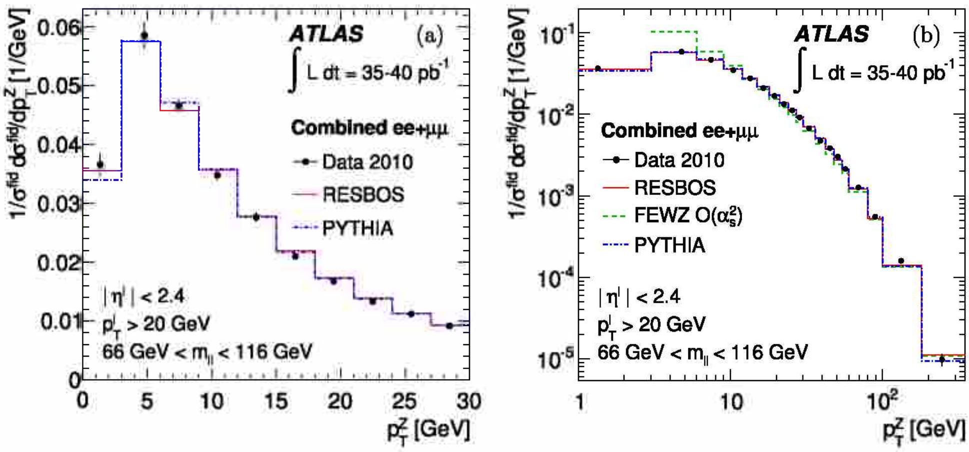

Fig. 3. The combined normalized differential cross section at Z/γ^* propagator level as a function of p_T^Z for (a) the range $p_T^Z < 30$ GeV and (b) the full range compared to the predictions of Resbos, Pythia, and Fewz at $\mathcal{O}(\alpha_S^2)$. The error bars shown include statistical and systematic uncertainties. For the combination, the ee ($\mu\mu$) channel contributes with an integrated luminosity of 35 pb^{-1} (40 pb^{-1}). At low p_T^Z the Fewz prediction diverges and is omitted.

Table 2
The combined normalized differential cross section at Z/γ^* propagator level, $1/\sigma^{\text{fid}}\, d\sigma^{\text{fid}}/dp_T^Z$, as a function of the average Z/γ^* transverse momentum $\langle p_T^Z \rangle$ with relative statistical and total systematic uncertainties. The multiplication with the inverse acceptance correction A_c^{-1} (given with uncertainties, "unc.") yields the normalized differential cross section $1/\sigma^{\text{tot}}\, d\sigma^{\text{tot}}/dp_T^Z$ extrapolated to the full lepton acceptance. The data can be obtained electronically through the HepData repository [43].

$\langle p_T^Z \rangle$ (GeV)	$\frac{1}{\sigma^{\text{fid}}}\frac{d\sigma^{\text{fid}}}{dp_T^Z}$ (GeV^{-1})	stat. (%)	syst. (%)	A_c^{-1}	unc. (%)
1.3	0.0366	2.0	4.7	1.047	3.7
4.8	0.0586	1.5	3.6	1.029	1.8
7.5	0.0466	1.7	1.5	1.014	1.5
10	0.0348	1.9	1.6	0.999	1.5
13	0.0277	2.2	1.7	0.999	1.4
16	0.0210	2.5	1.7	0.990	1.5
19	0.0167	2.8	1.8	0.989	1.5
22	0.0133	3.1	1.9	0.990	1.5
25	0.0112	3.4	2.0	0.994	2.3
28	0.0092	4.0	2.1	0.988	2.3
33	0.0067	3.2	2.1	0.987	3.2
39	0.0047	3.8	2.3	0.979	3.9
45	0.0038	4.2	2.4	0.965	4.3
51	0.0030	4.9	2.5	0.950	4.4
57	0.0021	5.7	2.7	0.938	5.3
69	0.0013	4.0	2.8	0.910	5.3
89	$5.5 \cdot 10^{-4}$	6.1	3.1	0.894	5.3
132	$1.6 \cdot 10^{-4}$	5.9	3.7	0.826	5.4
245	$9.8 \cdot 10^{-6}$	15.6	5.4	0.672	5.6

ties due to the unfolding procedure and QED FSR are considered to be common for the two channels. The minimization yields a χ^2/d.o.f. = 17.0/19 indicating the excellent compatibility of the electron and muon data.

The combined measurement of the normalized differential cross section within the fiducial lepton acceptance as a function of p_T^Z, $1/\sigma^{\text{fid}}\, d\sigma^{\text{fid}}/dp_T^Z$, is shown in Fig. 3 and Table 2. In addition, the acceptance corrections A_c needed to extrapolate the measurement to full lepton acceptance, but keeping the mass range 66 GeV $< m_{\ell\ell} <$ 116 GeV, are reported. They are determined using Pythia and the MRST2007LO* PDF set. The acceptance for the inclusive fiducial cross section is 0.48. However, the acceptance corrections A_c for the normalized differential cross section are within 10% of 1.0 for the bins with $p_T^Z < 80$ GeV. The uncertainty on A_c is estimated by: reweighting the Pythia prediction using the HERAPDF1.0 [49] and CTEQ6.6 [31] parton distribution functions; propagating the CTEQ6.6 PDF error eigenvector sets; and by taking into account the difference to the predictions obtained with Mc@nlo, Resbos, and Fewz.

In Fig. 4, the measurement within the fiducial acceptance is compared with predictions of pQCD calculations and of various event generators introduced above. The $\mathcal{O}(\alpha_S)$ and $\mathcal{O}(\alpha_S^2)$ pQCD predictions of the p_T^Z dependent cross section are obtained with Fewz v2.0 [7] and the MSTW2008 PDF sets [50]. The inclusive cross section, which is used to normalize the prediction, is calculated in the same way. The uncertainties on the normalized predictions are evaluated by variation of the renormalization and factorization scales by factors of two around the nominal scale $\mu_R = \mu_F = M_Z$ with the constraint $0.5 \leqslant \mu_R/\mu_F \leqslant 2$, by variation of α_S within a range corresponding to 90% confidence level limits [51], and by using the PDF error eigenvector sets at 90% confidence level. They amount to $\sim 10\%$ and $\sim 8\%$ for the $\mathcal{O}(\alpha_S)$ and $\mathcal{O}(\alpha_S^2)$ prediction, respectively, with a dominant contribution of 9% and 6.5% from the scale variations. In contrast to the Z/γ^* inclusive cross section, the prediction of the p_T^Z distribution suffers from substantial scale uncertainties indicating non-negligible missing higher order corrections. For $p_T^Z > 18$ GeV, the pQCD prediction receives an $\mathcal{O}(\alpha_S^2)$ correction of 26–36%. Despite this correction, the $\mathcal{O}(\alpha_S^2)$ prediction undershoots the data by about 10%, which is comparable to the size of the scale uncertainty. This deficit is smaller compared to the 15–25% difference observed at the Tevatron [25,26]. At low boson transverse momenta, where fixed order pQCD calculations are not expected to give an adequate description of the cross section, the disagreement increases rapidly towards vanishing p_T^Z.

In addition, the measurement is compared to the predictions of Resbos and various event generators. The consistency with the data is verified with a χ^2 test which uses the χ^2 definition also used for the combination of the ee and $\mu\mu$ decay channels.

The Resbos [13] prediction, which combines resummed and fixed order pQCD calculations, is based on the CTEQ6.6 [31] PDF set and a resummation scale of m_Z. It is verified that the different PDF sets used for the Fewz and Resbos predictions lead to differences below 3%. Resbos shows good agreement with the measurement over the entire p_T^Z range (χ^2/d.o.f. = 21.7/19), indicating the importance of resummation even at relatively large p_T^Z. However, its predictions are slightly higher than the data for p_T^Z values in the range of 10 GeV to 40 GeV and slightly lower above 40 GeV.

The Alpgen [19] and Sherpa [20] generators consider processes with up to five additional hard partons associated with the pro-

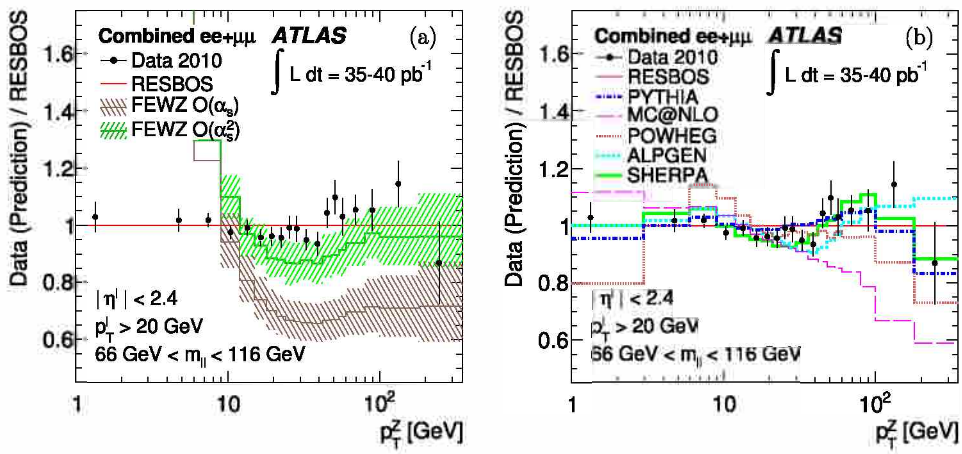

Fig. 4. Ratios of the combined data and various predictions over the Resbos prediction for the normalized differential cross section as a function of p_T^Z: (a) Fewz predictions at $\mathcal{O}(\alpha_S)$ and $\mathcal{O}(\alpha_S^2)$; (b) predictions from the generators Pythia, Mc@nlo, Powheg, Alpgen and Sherpa. The Fewz predictions are shown with combined scale, α_S, and PDF uncertainties. The data points are shown with combined statistical and systematic uncertainty. At low p_T^Z the $\mathcal{O}(\alpha_S)$ and $\mathcal{O}(\alpha_S^2)$ predictions of Fewz diverge and are omitted.

duced boson and give a good description of the entire measured spectrum, up to large p_T^Z, with χ^2/d.o.f. of 31.9/19 and 16.8/19, respectively. Here, the enhancement of the cross section compared to the $\mathcal{O}(\alpha_S^2)$ prediction can be attributed to processes with large parton multiplicities [52], which correspond to tree-level diagrams of higher order in the strong coupling. Sherpa v1.2.3 and Alpgen v2.13 are used, with the latter being interfaced to Herwig v6.510 [16] for parton shower and fragmentation into particles, and to Jimmy v4.31 [32] to model underlying event contributions. For Alpgen, the CTEQ6L1 [53] PDF set is employed and the factorization scale is set to $\mu_F^2 = m_{\ell\ell}^2 + \sum p_T^2$, where the sum extends over all associated partons. The Sherpa prediction uses the CTEQ6.6 PDF set and $\mu_F^2 = m_{\ell\ell}^2 + (p_T^Z)^2$.

The predictions of the parton shower event generators Pythia and Mc@nlo are based on the simulated samples as described above. Fig. 4b also shows the predictions of Powheg v1.0 [18] interfaced to a Pythia version with an underlying event tune to Tevatron and 7 TeV pp collision data [54]. Whereas Mc@nlo (χ^2/d.o.f. = 111.6/19) and Powheg (χ^2/d.o.f. = 100.4/19) deviate from the data at low and high p_T^Z, Pythia describes the measurement well over the entire range of boson transverse momentum (χ^2/d.o.f. = 17.9/19).

In summary, the Z/γ^* transverse momentum differential distribution has been measured up to $p_T^Z = 350$ GeV for electron and muon pairs with invariant masses 66 GeV $< m_{\ell\ell} <$ 116 GeV produced in pp collisions at $\sqrt{s} = 7$ TeV based on integrated luminosities of 35 pb^{-1} and 40 pb^{-1}, respectively, recorded with the ATLAS detector. Resbos describes the spectrum well for the entire p_T^Z range. At $p_T^Z > 18$ GeV, the central Fewz $\mathcal{O}(\alpha_S^2)$ prediction underestimates the data by about 10%, which is comparable to the size of the combined experimental and theoretical uncertainty. The measurement is compared to predictions of various event generators and a good agreement with Sherpa, Alpgen, and Pythia is found. Except for the lowest p_T^Z values, the measurement is limited by statistics rather than systematic uncertainties. The systematic uncertainties are also mostly limited by the size of the data sample and are expected to improve with increasing integrated luminosity.

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D'Onofrio [73], A. D'Orazio [132a,132b], P.V.M. Da Silva [23a], C. Da Via [82], W. Dabrowski [37], T. Dai [87], C. Dallapiccola [84], M. Dam [35], M. Dameri [50a,50b], D.S. Damiani [137], H.O. Danielsson [29], D. Dannheim [99], V. Dao [49], G. Darbo [50a], G.L. Darlea [25b], C. Daum [105], J.P. Dauvergne [29], W. Davey [86], T. Davidek [126], N. Davidson [86], R. Davidson [71], E. Davies [118,c], M. Davies [93], A.R. Davison [77], Y. Davygora [58a], E. Dawe [142], I. Dawson [139], J.W. Dawson [5,*], R.K. Daya [39], K. De [7], R. de Asmundis [102a], S. De Castro [19a,19b], P.E. De Castro Faria Salgado [24], S. De Cecco [78], J. de Graat [98], N. De Groot [104], P. de Jong [105], C. De La Taille [115], H. De la Torre [80], B. De Lotto [164a,164c], L. De Mora [71], L. De Nooij [105], M. De Oliveira Branco [29], D. De Pedis [132a], P. de Saintignon [55], A. De Salvo [132a], U. De Sanctis [164a,164c], A. De Santo [149], J.B. De Vivie De Regie [115], S. Dean [77], D.V. Dedovich [65], J. 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