PROCEEDINGS OF SCIENCE

Measurement of the transverse momentum of the Z boson and NLO MC tuning

Homero MARTINEZ∗†
INFN Pavia
E-mail: homero.martinez@pv.infn.it

A measurement of the Z/γ^* boson transverse momentum spectrum in proton-proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV, performed by the ATLAS collaboration at LHC, is reported. The measurement is sensitive to soft resummation effects for small momentum transfers and to perturbative effect for large momentum transfers, probing QCD in a unique way. The data are used to tune parton shower Monte Carlo simulations.

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∗Speaker.
†On behalf of the ATLAS collaboration

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1. Introduction

W and Z bosons are produced in hadronic collisions with non-zero transverse momentum (p_T), due to the emission of additional partons in the initial state, in addition to the intrinsic p_T of the partons participating in the hard process. Measurements of the p_T spectrum offer insight into the dynamical effects of the strong interaction, namely, perturbative predictions and parton density functions (high p_T range) and resummation and parton shower models (low p_T range).

The p_T spectrum of the Z boson, reconstructed using the electron and muon decay channels, provide a precise signal with very low background. In this document, we summarize a measurement of this variable, done by the ATLAS collaboration [1], using 4.7 fb^{-1} of LHC proton-proton collision data at $\sqrt{s} = 7$ TeV. The measurement [2] reaches a better precision and a larger p_T^Z range (800 GeV) in comparison to previous measurements.

2. Experimental procedure and uncertainties

The normalized differential cross section as a function of p_T^Z is defined as $(1/\sigma^{\mathrm{fid}})(\mathrm{d}\sigma^{\mathrm{fid}}/\mathrm{d}p_\mathrm{T}^Z)$, where σ^{fid} is the inclusive $pp \to Z/\gamma^* + X$ cross section measured within the fiducial acceptance defined by requiring $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.4$ for the decay leptons; the invariant mass of the pair must satisfy $66 < m_{\ell\ell} < 116$ GeV. In addition to the rapidity-inclusive measurement, the measurement is performed for $0 \leq |y^Z| < 1$, $1 \leq |y^Z| < 2$ and $2 \leq |y^Z| < 2.4$.

The total sample consists of 1228863 $Z/\gamma^* \to e^+e^-$ and 1816784 $Z/\gamma^* \to \mu^+\mu^-$ candidate events. The background events are subdivided in electroweak (τ and W boson, diboson), single top and $t\bar{t}$ production, and multijet events, where real or fake leptons pass the selection. The electroweak and top background are estimated using Monte Carlo (MC) simulations, normalized to data luminosity. The multijet background is estimated using data-driven methods.

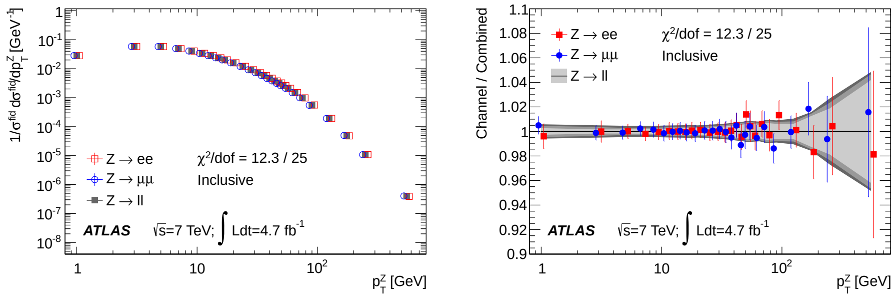
The estimated background is subtracted from the reconstructed p_T^Z distributions, which is subsequently corrected for resolution, efficiency and QED final state radiation (FSR) effects, using an iterative bayesian unfolding method [3, 4, 5] with three iterations. The response matrix needed by the unfolding procedure is constructed using signal MC samples obtained from the NLO generator POWHEG [6] interfaced with PYTHIA6 [7] for the parton shower. The prior assumed for the p_T^Z distribution in the unfolding procedure is obtained from the PYTHIA6-AMBT1 tune [8].

The dominant experimental uncertainties in the electron channel arise from the electron energy scale and resolution, with a combined contribution of typically 0.3% per bin between 4 GeV and 70 GeV, and about 2% at the end of the spectrum. In the muon channel, the trigger, reconstruction and isolation efficiency corrections contribute an uncertainty of 0.6% on average, spanning 0.2% to 1.7% across the measurement range, and the momentum scale and resolution uncertainties amount to 0.2%, except in the last three p_T^Z bins where they stay below 1.5%.

The dominant contribution to the systematic uncertainties for both channels comes from the unfolding method. Two effects are addressed: the bias of the result towards the prior, which gives an effect of less than 0.1% up to 100 GeV, and less than 1.3% for the rest of the distribution; and the dependence of the result on the theoretical calculation used to determine the response matrix, which results in a systematic uncertainty of about 0.3% over the whole p_T^Z range.

3. Results

The electron- and muon-channel cross sections are combined using χ^2 minimization, following the best linear unbiased estimator prescription (BLUE) [9, 10]. The combined precision for the y^Z inclusive measurement is between 0.5% and 1.1% for $p_T^Z < 150$ GeV, rising to 5.5% towards the end of the spectrum. The combination has $\chi^2/\mathrm{dof} = 12.3/25$ (χ^2 per degree of freedom). The individual channel measurements are compared to the combined result in figure 1.



(a) (b)

Figure 1: (a) Measured inclusive normalized cross section $(1/\sigma^{\mathrm{fid}})(\mathrm{d}\sigma^{\mathrm{fid}}/\mathrm{d}p_T^Z)$ as a function of p_T^Z for the electron and muon channels and the combined result, (b) ratio of the electron and muon channels to the combined result. The uncertainty bands represent the statistical, total uncorrelated and total uncertainties.

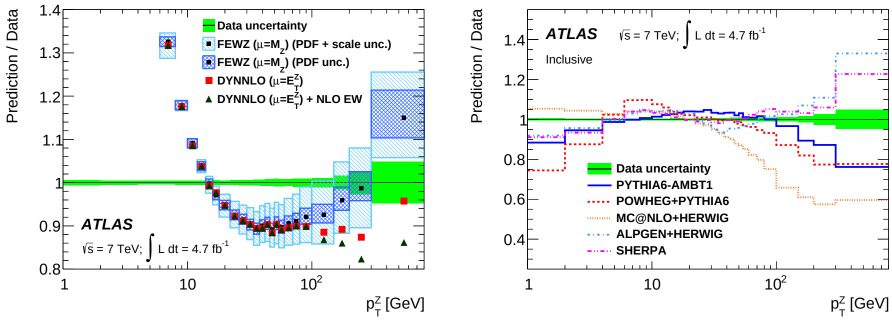
4. Comparison to QCD predictions

In figure 2, the combined result is compared to different theoretical predictions (the figures show the prediction-to-measurement ratio). Figure 2a shows the comparisons to the FEWZ [11, 12, 13] and DYNNLO [14, 15] calculations, which are based on perturbative QCD (pQCD) up to second order (NNLO) in the strong coupling constant (α_s^2). The uncertainty shown on the predictions contains PDF uncertainties and renormalization and factorization scale variations. The influence of the QCD scale choice is studied with DYNNLO by using the alternative dynamic scale. The resulting p_T^Z shape is in better agreement with the data for $p_T^Z > 30$ GeV. NLO electroweak corrections [16] are applied to the dynamic-scale prediction and lead to a decrease of the cross section of 10% in the highest p_T^Z bin.

Figure 2b shows the comparison to different MC generator predictions. The PYTHIA and POWHEG generators agree with the data to within 5% in the $2 < p_T^Z < 60$ GeV range, and to within 20% over the full range. MC@NLO [17] shows a similar level of agreement with the data for $p_T^Z < 30$ GeV but develops a discrepancy up to around 40% at the end of the spectrum. SHERPA [18] and ALPGEN [19] agree with the data to within about 5% for $5 < p_T^Z < 200$ GeV, but tend to overestimate the distribution near the end of the spectrum.

5. Tuning of PYTHIA8 and POWHEG+PYTHIA8

The parton shower tunes are performed in order to determine the sensitivity of the measured p_T^Z cross sections to parton shower model parameters in state-of-the-art MC generators, and to

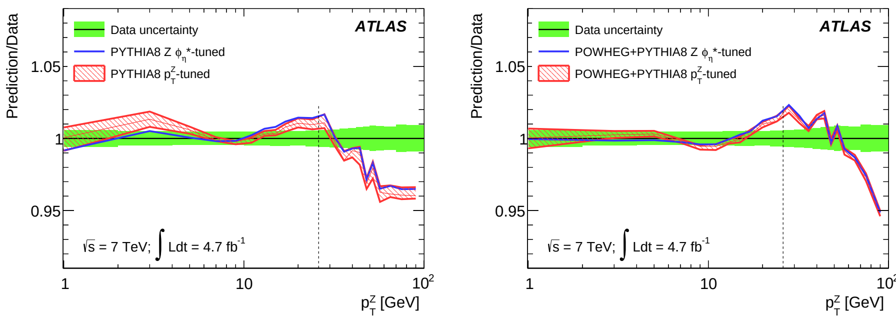


(a) (b)

Figure 2: Comparison of the p_{T}^{Z} distributions predicted by different computations with the combined measurement, inclusively in y^{Z}. a) FEWZ and DYNNLO, b) different MC generators.

constrain the models by trying to achieve precise predictions of vector boson production. The ATLAS $\phi_{\eta}^{\star}$ measurement [20] is also exploited as it is highly correlated to p_{T}^{Z} and is hence sensitive to the same model components[1]. The tunes are performed using the Professor [22] package.

The sensitivity of the generator parameters to the p_{T}^{Z} and $\phi_{\eta}^{\star}$ measurements is probed by performing tunes of PYTHIA8 and POWHEG+PYTHIA8 to each measurement separately. The results show that both measurements have comparable sensitivity and yield compatible tuned parameter values. The tuning uncertainty is obtained from variations of the eigenvector components of the parameters error matrix. Figure 3 shows that the tuned predictions agree with the measured cross sections within 2% for $p_{\mathrm{T}}^{Z} < 50$ GeV.



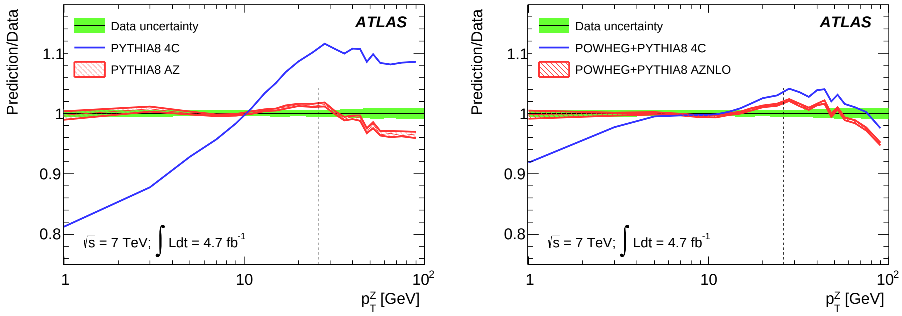
(a) (b)

Figure 3: Comparison of the PYTHIA8 (a) and POWHEG+PYTHIA8 (b) tuned predictions based on the $\phi_{\eta}^{\star}$ and p_{T}^{Z} measurements.

The final tune optimally combines the most precise independent single measurements, namely the muon channel p_{T}^{Z} measurement, and the electron channel $\phi_{\eta}^{\star}$ measurement. Figure 4 shows the comparison of the tuned predictions to the data. The final tunes are referred to as AZ and AZNLO for PYTHIA8 and POWHEG+PYTHIA8 respectively. The tuned predictions agree with the

[1] $\phi_{\eta}^{\star}$ is defined as $\phi_{\eta}^{\star} \equiv \tan\left[(\pi - \Delta\phi)/2\right]\sin(\theta_{\eta}^{*})$, where $\Delta\phi$ is the azimuthal angle between the leptons, and θ_{η}^{*} is a measure of the scattering angle of the leptons [21].

measurement to better than 2% in the range used for the tuning, and below $p_T^Z = 50$ GeV. In the figures, the tuned predictions are also compared to the 4C tune, defined in [23].



(a) (b)

Figure 4: Comparison of tuned predictions to the p_T^Z differential cross sections. (a) Comparison of the PYTHIA8 generator with the 4C and AZ tunes to the muon-channel p_T^Z data and electron-channel $\phi_\eta^\star$ data. (b), comparison of the POWHEG+PYTHIA8 set-up with the 4C and AZNLO tunes to the same data.

6. Conclusion

A measurement of the Z/γ^* transverse momentum spectrum in the $Z/\gamma^* \to e^+e^-$ and $Z/\gamma^* \to \mu^+\mu^-$ channels with the ATLAS detector is presented, using 4.7 fb^{-1} of LHC proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 7$ TeV. Normalized differential cross sections as a function of p_T^Z are measured for the range $0 < p_T^Z < 800$ GeV and the individual channel results are combined. The measurement is performed inclusively in rapidity, and for $0 \leq |y^Z| < 1$, $1 \leq |y^Z| < 2$ and $2 \leq |y^Z| < 2.4$. The large data sample allows a fine granularity in p_T^Z with a typical uncertainty on the combined result better than 1% for $p_T^Z < 100$ GeV, rising to 5% towards the end of the spectrum.

The cross-section measurements are compared to pQCD, resummed predictions and MC generators, with different levels of agreement. The p_T^Z and $\phi_\eta^\star$ measurements were used to tune the PYTHIA8 and POWHEG+PYTHIA8 generators. Both measurements can be interpreted consistently in terms of the Z/γ^* bosons transverse momentum distribution and provide similar sensitivity to parton shower model parameters.

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