PROCEEDINGS OF SCIENCE

Measurement of the Z boson transverse momentum: directly and using the ϕ^*_η variable with ATLAS

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A measurement of angular correlations in Drell-Yan lepton pairs via the ϕ^*_η observable at the LHC using ATLAS data at $\sqrt{s} = 7$ TeV is presented. This variable is determined exclusively from the measured lepton directions and probes the same physics as the Z/γ^* boson transverse momentum (p_T) with a better experimental resolution, especially for low transverse momentum. The measurements using ϕ^*_η and the direct measurement of p_T are compared to predictions based on QCD calculations and predictions from different Monte Carlo event generators.

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PoS(DIS 2013)131

The transverse momenta of Z bosons produced via the Drell Yan mechanism have been studied at the LHC using data collected with the ATLAS detector [1]. At the leading order (LO) approximation the Z boson is produced without transverse momentum, such that the leptons are exactly back-to-back. However, experimentally Z bosons are found to have non-zero p_T. The first contribution to the Z boson transverse momentum is known as the intrinsic momentum, which refers to the momenta of partons within the proton rest frame. Another effect comes from radiation of quarks and gluons from the initial-state partons. In this context the Z boson transverse momentum provides an ideal testing ground for QCD. Most often the Z boson is produced with a small p_T when one or both of the initial quarks undergo initial state gluon radiation. This production cross section is described by analytic resummation of large logarithms to all orders in α_s or by parton shower generators. The Z boson can also be created with a large p_T. In this case the Z boson recoils against an energetic quark or gluon. Here the production cross section is expected to be well described by perturbative QCD. A precise understanding of the p_T^Z spectrum is also necessary to improve modeling of W boson production, which is essential for a precise measurement of the W mass.

The precision of direct measurements of the Z spectrum at low p_T^Z at the LHC and Tevatron is limited by the experimental resolution and the systematic uncertainties, which also affect the choice of bin widths. In recent years, additional observables have been investigated [2, 3]. The p_T^Z variable can be split into two components with respect to an event axis defined as, $\hat{t} = (p_T^{(1)} - p_T^{(2)})/|p_T^{(1)} - p_T^{(2)}|$, where $p_T^{(1)}$ and $p_T^{(2)}$ are the lepton transverse momentum (Figure 1). The component transverse to the event axis is denoted by a_T and the aligned component is denoted by a_L. The a_T variable was found to be less sensitive to the lepton p_T resolution than p_T^Z. Futher improvement of the physics sensitivity and experimental resolution in the low p_T^Z region can be achieved by measuring the angular correlation of the lepton pairs. The azimuthal opening angle between the two leptons, $\Delta\phi$, is primarily sensitive to the same component of p_T^Z as a_T. The translation from the a_T variable to $\Delta\phi$ depends on the scattering angle of the leptons, thus $\Delta\phi$ is less directly related to p_T^Z than a_T. The ϕ^*_η variable was found to be an optimal to measure the Z transverse momentum:

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

where $\phi_{acop} \equiv \pi - \Delta\phi$ and $cos\theta^*_\eta \equiv \tanh[\frac{\eta^- - \eta^+}{2}]$, η^- and η^+ are the pseudorapidities[1] of the negatively and positively charged lepton, respectively. This ϕ^*_η variable depends on two angles defined by the direction of the two leptons, such that ϕ^*_η is experimentally well measured compared to any quantities that rely on the momenta of the leptons. The variable ϕ^*_η is correlated to p_T^Z and probes the same physics.

The Z boson transverse momentum distribution using the ϕ^*_η variable is analysed using 4.6 fb^{-1} of $\sqrt{s} = 7$ TeV ATLAS data collected in 2011 [4]. The direct Z boson transverse momentum measurement uses 35 pb^{-1} of electron and 40 pb^{-1} of muon 2010 data [5]. Both measurements

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

PoS(DIS 2013)131

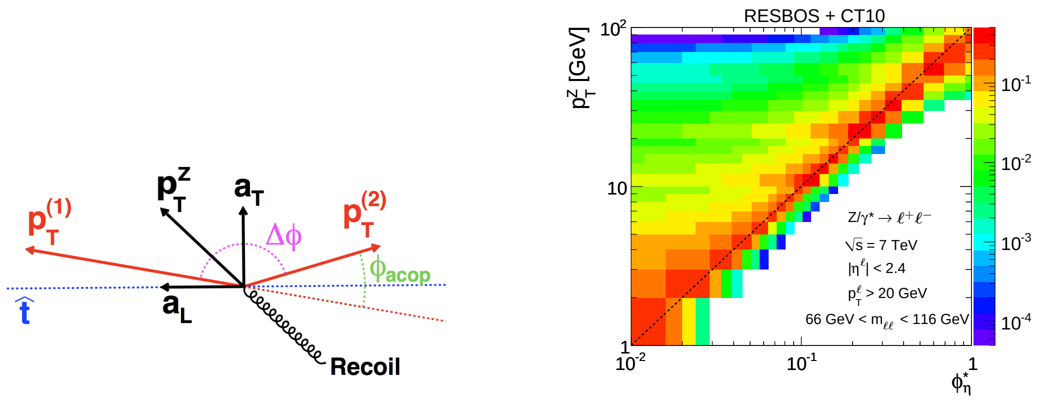

Figure 1: a Graphical illustration in the plane transverse to the beam direction of the variables used to analyze the dilepton transverse momentum distribution (on the left). Correlation matrix between the p_T^Z and ϕ^*_η variables (on the right). Values of ϕ^*_η from 0 to 1 probe the p_T distribution up to $\sim$ 100 GeV [3, 4].

are implemented in the electron and muon channels, with similar lepton selections. The p_T of both leptons is required to be more than 20 GeV - and in the electron channel for ϕ^*_η measurements, due to the higher online electron trigger threshold, the p_T of the leading electron must be more than 25 GeV. The pseudorapidity of the leptons is less than 2.4. Electrons in the calorimeter transition region, 1.37<$|\eta|$<1.52, are excluded. The Z boson events are selected by requiring two oppositely charged same-flavour leptons with an invariant mass between 66 and 116 GeV. After these selection requirements $1.22 \cdot 10^6$ dielectron and $1.69 \cdot 10^6$ dimuon candidate events are found in 2011 data, with corresponding samples 8923 and 15060 in 2010 data. The normalised differential cross section is measured in the fiducial region defined by dilepton invariant mass $66 < m_{\ell\ell} < 116$ GeV, pseudorapidity $|\eta| < 2.4$ and lepton transverse momentum more than 20 GeV. Monte Carlo (MC) simulations are used to calculate efficiencies and acceptances for the signal processes and to unfold the measured spectra for detector effects and for different levels of QED final state radiation (FSR). Generated events are reweighted as a function of p_T to the predictions from RESBOS [6–8], which describes the p_T spectrum more accurately.

Even after the full selection, the final event samples contain a background contribution from non-signal events. The sources of background can be split in two: electroweak background including a contribution from $t\bar{t}$ production and QCD multi-jet background. In the low ϕ^*_η and p_T regions the QCD background dominates. This background comes from hadronic jets, which are falsely identified as electrons or muons. This background cannot be simulated by MC with sufficient statistics and in this case the background is determined using data-driven methods. In the high p_T and ϕ^*_η regions for both electron and muon channels, the main background arises from $t\bar{t}$ production. The electroweak background is estimated using Monte Carlo simulation. The total fraction of background events for both channels is relatively small - for the measurement using the ϕ^*_η variable it is $(0.56 \pm 0.28)\%$ in the muon channel and $(0.61 \pm 0.31)\%$ for the electron channel, and for the direct p_T measurement the values are $(0.40 \pm 0.28)\%$ and $(1.5 \pm 0.6)\%$ respectively. The QCD multi-jet background represents half of the total background in both channels.

The differential cross section is evaluated from the observed data events in each bin after subtraction of the estimated background events. The cross-section measurement relies on various

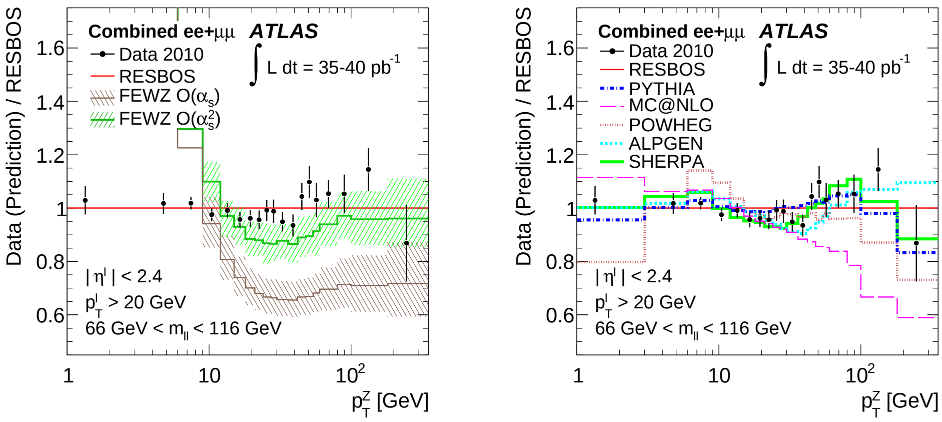

Figure 2: Ratios of the combined data and predictions from the various event generators to the RESBOS prediction for the normalized differential cross section as a function of p_T^Z [5].

corrections applied to the data and MC. Each correction has statistical and systematic uncertainties, which need to be propagated to the systematic uncertainty of the cross section. For the direct measurement the main systematic sources come from the lepton efficiencies and the unfolding procedure and the uncorrelated systematics come mostly from the MC statistics and QED FSR. For the ϕ^*_η measurement the experimental uncertainty is very small, and is dominated by the QED FSR uncertainty. In order to improve statistical accuracy and reduce the systematic errors, the electron and muon cross section measurements are combined, for both p_T^Z and Z ϕ^*_η measurements. The two decay channels are combined at the "Born" level using a χ^2 minimisation method, which takes into account all sources of correlated and uncorrelated uncertainties. The combination method also allows the agreement between the two channels to be quantified. For both measurements very good consistency is found between elecron and muon data: the χ^2 value for the Z ϕ^*_η measurement is $\chi^2/n_{dof} = 33.2/34$, and for p_T^Z it is $\chi^2/n_{dof} = 17.0/19$.

The normalised differential cross section as a function of p_T^Z has been measured up to 350 GeV in 19 p_T bins. The measurement is compared to predictions from RESBOS, FEWZ [9, 10] and various event generators in Figure 2. RESBOS shows good agreement with the measurement over the entire p_T^Z range, indicating the importance of ressumation even at relatively large p_T. The FEWZ prediction is implemented at both NLO and NNLO. The uncertainties on the normalized predictions are evaluated by variation of renormalisation and factorisation scales by factors of two around the nominal scale which is set to the mass of the Z boson. FEWZ at NNLO agrees with the data within the uncertainty. The LO generators give a good description of the entire measured spectrum. A worse description is given by NLO generators which deviate from the data at low and high p_T^Z.

The normalised differential cross section as a function of ϕ^*_η has been measured in 34 ϕ^*_η bins, with ϕ^*_η up to ∼3, which is approximately the same transverse momentum region that was measured with the p_T variable, see Figure 3. The measured cross section is compared to RESBOS predictions, which deviate from the data by up to 5%, within the RESBOS systematic uncertainty. The prediction obtained with FEWZ at NNLO undershoots the data by 10%. The data are also compared to predictions obtained using a NNLL resummation technique matched to fixed order

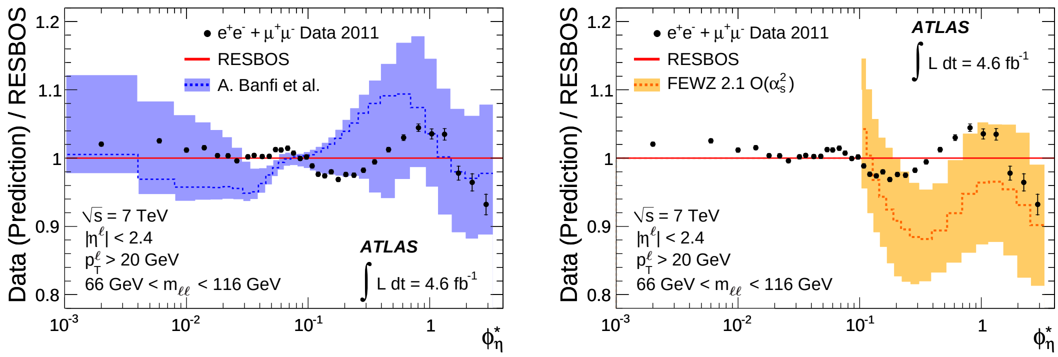

Figure 3: The ratio of the combined normalised differential cross section to RESBOS predictions as a function of ϕ^*_η [4].

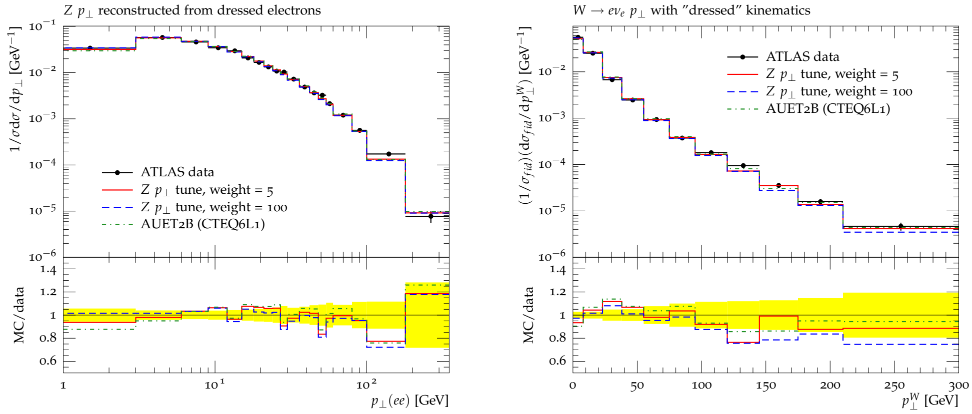

Figure 4: Comparison of the ATLAS p_T^Z and p_T^W measurements with the Pythia6 predictions obtained with the AUET2B tune before (green) and after the inclusion of the ATLAS p_T^Z data (red and blue). The impact of the p_T^Z data on the tune parameters is quantified by its weight relative to the other tune observables. The yellow band on the ratio plots illustrates the data uncertainty [14].

calculation [11]. The uncertainty takes into account ressumation scale variations. The Z ϕ^*_η cross section was also measured double-differentially for three independent bins of boson rapidity.

Both measurements are generally well described by theory. The discrepancy between the data and the MC predictions can be addressed by tuning the event generator parameters corresponding to the production model. The ATLAS p_T^Z data were included to the Pythia6 [12] AUET2B tune [13]. Figure 4 shows the Pythia6 predictions for the p_T^Z and p_T^W spectra, using the AUET2B tune standalone and including the p_T^Z data [14]. The tune with the higher impact of the p_T^Z data on the tune parameters improves the description of the spectra at low p_T, where data uncertainties are smallest.

To summarise, the Z boson transverse momentum has been measured by ATLAS as a function of ϕ^*_η and p_T. The experimental uncertainty for the Z ϕ^*_η measurement is smaller than the present theoretical uncertainty. The measurements can be used to improve the modeling of Z and W boson production by MC event generators. Improving the description of the p_T^W spectrum is important to derive a systematic uncertainty for the W mass measurement.

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PoS(DIS 2013)131