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Measurements of inclusive and associated jet W and Z production with the ATLAS detector

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The production of the $W^{\pm}$ and Z bosons at the Large Hadron Collider is a sensitive test of the Standard Model. Precise total and differential cross-section measurements by the ATLAS experiment are presented. The results are compared to Monte Carlo simulations and to predictions computed at up to next-to-next-to-leading order quantum-chromo-dynamics (QCD) for different sets of parton distribution functions. A measurement of angular correlations in Drell-Yan lepton pairs for neutral current process via the ϕ^*_η observable is also presented. This variable probes the same physics as the Z/γ^* boson transverse momentum (p_{T}) with a better experimental resolution. The measurement using ϕ^*_η and the direct measurement of vector boson p_{T} are compared to predictions based on QCD calculations and predictions from different Monte Carlo event generators. The production of jets in association with a W or Z boson is an important process to study QCD in a multi-scale environment. The cross sections, differential in several kinematics variables, have been measured up to high jet multiplicities and compared to high-order QCD calculations. The exclusive processes of W+b and W+c production have also been measured with high precision and cross sections are compared to state-of-the-art high-order QCD calculations.

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1. Introduction

ATLAS [1] has carried out multiple measurements of vector boson production both inclusively and with associated light or heavy flavour jets at the Large Hadron Collider (LHC). Events containing a W or a Z boson provide clear experimental signatures in the leptonic decay channels and are produced abundantly at the LHC, thanks to their large cross sections. These events can be considered as a test bench for probing high-order quantum-chromo-dynamics (QCD) as well as measuring electro-weak parameters and constraining parton distribution functions (PDFs). These measurements have reached high experimental precision and allow stringent comparisons with theoretical predictions to be made.

The study of boosted vector boson production, i.e. with non-zero p_{T}, can be used to constrain theoretical models of perturbative QCD (pQCD): the high and low vector boson p_{T} regimes can probe high-order QCD corrections and resummation techniques, respectively. The studies of W or Z boson events where accompanying jets are explicitly reconstructed, either inclusively in jet flavour or exclusively as heavy-flavour jets, provide important tests of high-order QCD calculations, heavy-flavour production schemes, and can also be used to constrain PDFs. Furthermore, such processes constitute an important background to many searches for new phenomena. With the large LHC data-sets being available such measurements are carried out at higher jet multiplicities and higher scale regimes then previously.

The measurements presented here are based on the data collected by the ATLAS detector during the years 2010 and 2011 of LHC proton-proton collision running at 7 TeV centre-of-mass energy. The measurements are carried out separately for electron and muon channels, corrected to a common region in phase space and then combined.

2. W, Z inclusive production

The Z, W^+ and W^- production cross sections have been measured both inclusively and differentially [2] using about 35 pb^{-1} of 2010 data. Figure 1(a) shows the fiducial inclusive cross sections of W^+ and W^- bosons. The uncertainty is dominated by the 1% systematic uncertainty[1]. The measurement is compared to theoretical predictions obtained from next-to-next-to-leading-order (NNLO) FEWZ2.0 [3] with the MSTW2008 [4], HERAPDF1.5 [5], ABKM09 [6] or JR09 [7] NNLO PDF sets. The measurement, while in broad agreement with NNLO prediction, shows some tension between the different PDFs.

The Z, W^+ and W^- cross section measurements by ATLAS as a function of the pseudo-rapidity, η, of the decay lepton are used together with the deep inelastic scattering data from the H1 and ZEUS experiments at HERA as inputs to NNLO PDF fits performed with the HERAFitter framework [5][8]. The results of these fits are named $epWZ$ [9]. The fit which parametrises the anti-strange contribution $\bar{s}$ with two free strangeness parameters and assumes $s = \bar{s}$ shows better agreement with ATLAS data than the one with fixed $\bar{s}$ where the strange to down quark ratio is fixed to $\bar{s}/\bar{d} = 0.5$. The level of suppression of the strange sea can be determined from the free $\bar{s}$ fit by considering the ratio $r_s = 0.5(s+\bar{s})/\bar{d}$, which is found to be $1.00^{+0.25}_{-0.28}$ when evaluated at the initial scale of 1.9 GeV and parton momentum fraction x = 0.023. This is consistent with no

[1] excluding the 3.4% luminosity uncertainty.

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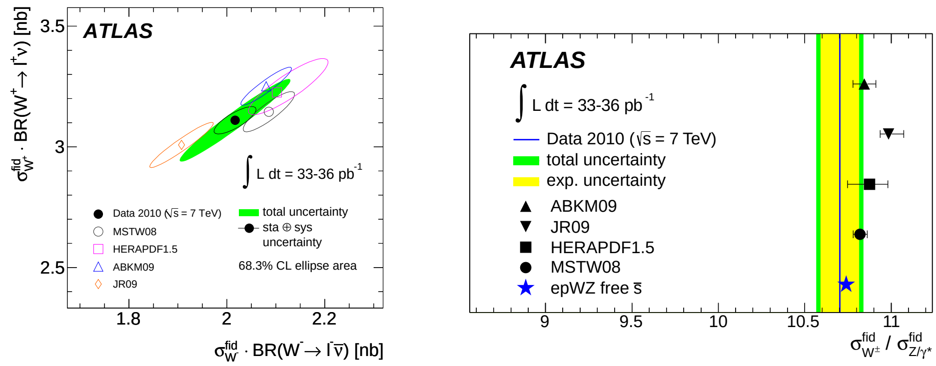


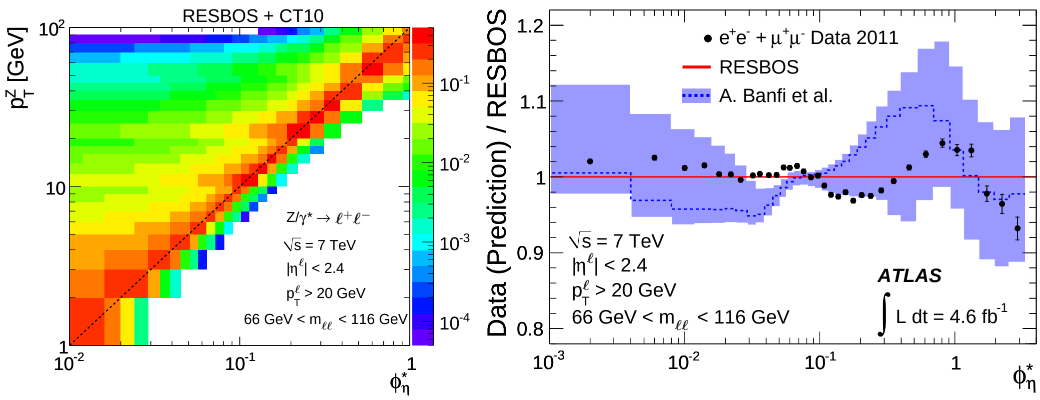
(a) (b)

Figure 1: Fiducial inclusive cross sections of the W^+ and the W^- bosons (a) [2] and the ratio of $W^\pm$ to Z/γ^* (b) [9]. The total uncertainty includes the luminosity systematic uncertainty. The theoretical predictions are obtained at NNLO with FEWZ2.0 and various NNLO PDFs.

suppression of the strange quark sea at very low x. The level of agreement of the epWZ fit with ATLAS data can be seen from the measurement of the ratio of $W^\pm$ to Z/γ^* fiducial cross sections, as in fig.1(b). The epWZ fit with free $\bar{s}$ better agrees with the ATLAS measurement than the other PDF fits with a suppressed $\bar{s}$ contribution.

3. Boosted W, Z

The measurement of the W and Z cross section as a function of the boson p_T is important for improving our understanding of Higgs boson production and the model uncertainty in precision measurements, e.g. the W mass. The ATLAS collaboration has published measurements of the W and Z p_T spectra using about 31 pb^{-1} of integrated luminosity [10][11] and compared them with theoretical predictions, such as LO and NLO Monte Carlo (MC) generators and analytic calculations at NNLO with and without NNLL resummation. Higher precision experimental measurements can be obtained by measuring the Z cross section as a function of the ϕ^*_η variable defined as $\phi^*_\eta \equiv \tan(\phi_{\rm acop}/2)\cdot\sin(\theta^*_\eta)$, where $\phi_{\rm acop} \equiv \pi - \Delta\phi$ and $\cos(\theta^*_\eta) \equiv \tanh[(\eta^- - \eta^+)/2]$, with $\Delta\phi$ being the difference in the azimuthal angle between the leptons, and $\eta^\pm$ being the pseudo-rapidity of each lepton. As such, ϕ^*_η is dependent only on the angles of the two leptons which can be measured with far better resolution than the momentum, particularly at low p_T. The variable is correlated with p_T^Z/m_{ll}, as shown in fig. 2(a), allowing the same physics to be probed. The normalised differential cross section measured in data by ATLAS [12] with 4.6 fb^{-1} of integrated luminosity is compared to theoretical predictions from an analytic QCD calculation published in ref. [13] and from RESBOS [14]. The first prediction matches NNLL resummation to an NLO QCD calculation from MCFM [15]; the second prediction matches NNLL resummation to an LO QCD calculation corrected with NLO/LO k-factors. Fig. 2(b) shows that the difference between the RESBOS prediction and the data is smaller than the RESBOS PDF uncertainty of about 4 – 6%. The analytical calculation describes the data less well than RESBOS, but is still overall in agreement within the relatively large theoretical uncertainty. It should be noticed that the experimental measurement is an order of magnitude more precise than theory.



(a) (b)

Figure 2: (a) Correlation matrix between ϕ^*_η and Z p_T variables, at Born level, for Z/γ^* in the fiducial region using RESBOS with CT10 PDF. (b) Ratio of normalised differential cross sections as function of ϕ^*_η from data and an analytical QCD calculation to RESBOS (see ref. [12]).

4. W, Z plus jets production

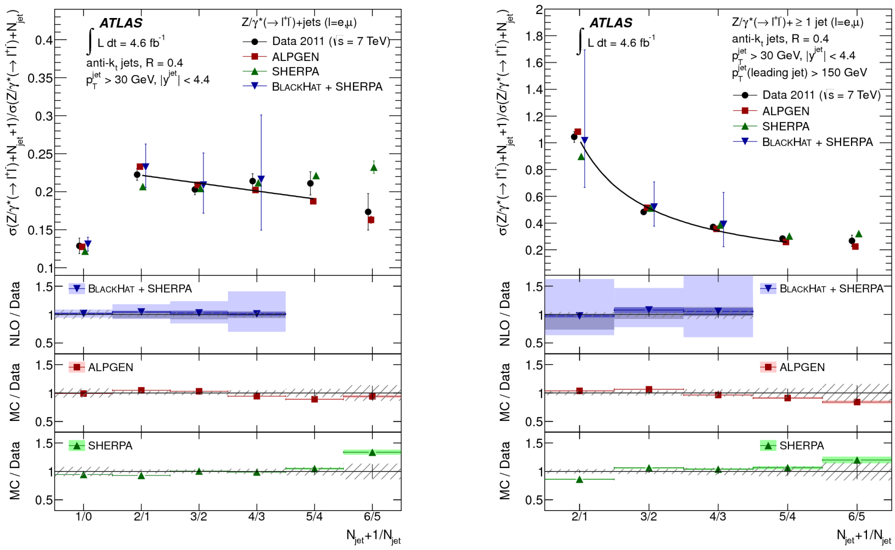
4.1 W, Z plus inclusive jets

The large data-set of 4.6 fb^{-1} allows the study of Z production with up to seven jets and jet p_T up to 700 GeV [16], where the jets are reconstructed in a large acceptance region in rapidity, $|y^{jet}| < 4.4$. The measurements are compared to NLO predictions from the BlackHat + SHERPA program [17][18][19] and LO predictions from ALPGEN [20] and SHERPA [21] MC generators.

Figure 3 shows the scaling patterns in Z+jet events by investigating $R_{(n+1)/n}$, the ratio of Z production with exactly $(n+1)$ jets to that with exactly n jets. Exclusive jet multiplicities are expected to be described by a combination of *Staircase scaling* in which $R_{(n+1)/n}$ is constant and *Poisson scaling* in which $R_{(n+1)/n}$ is inversely proportional to n. The symmetric jet selection, i.e. all jet $p_T > 30$ GeV, is used to investigate staircase scaling in fig. 3(a) whilst Poisson scaling is enhanced in fig. 3(b) by introducing a large scale difference between the leading jet ($p_T > 150$ GeV) and the sub-leading jets ($p_T > 30$ GeV). It is seen that both scaling relations are well described by the theoretical models. The measurement of these scaling properties will be useful in analyses searching for new particles beyond the Standard Model (SM), e.g. SUSY, which employ jet vetoes to discriminate between signal and Z+jets background, and assume scaling properties between low and high jet multiplicity to estimate the Z+jets background.

Z+jets events form an irreducible background to Higgs boson analyses, for example in the vector-boson-fusion (VBF) production channel. A study of Z+jets events with a VBF-like selection is carried out to study the modelling of Z+jets events as background to Higgs analysis. These events are selected by requiring two jets with large invariant mass ($m^{jj} > 350$ GeV) and large rapidity separation ($\Delta y^{jj} > 3.0$). Both ALPGEN and SHERPA MC generators provide a good description of the data within 5% accuracy in various observables.

The study of W boson production with jets is complementary to Z+jets, as it has larger statistics but also larger background contamination. A vast range of measurements of W+jets properties have been carried out using 36 pb^{-1}[22]. In particular a large deviation between fixed order pQCD



(a) (b)

Figure 3: Ratio of cross sections of successive jet multiplicities for Z+jet events. Staircase scaling is exhibited using the standard selection in (a) whilst Poisson scaling is enhanced in (b) by requiring the leading jet $p_{\mathrm{T}} > 150$ GeV [16].

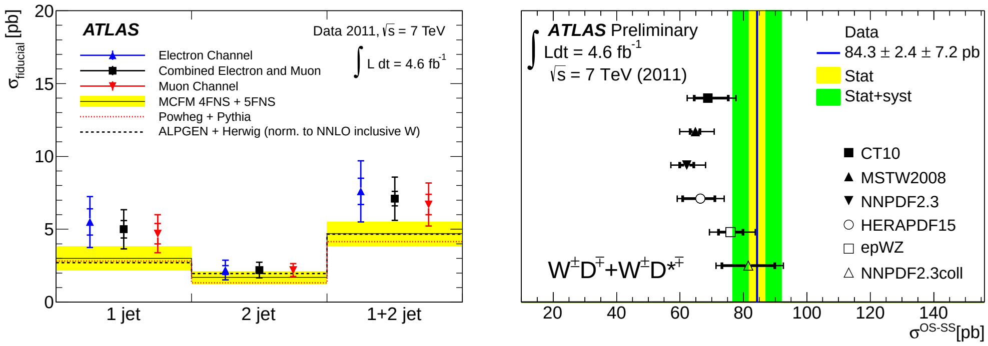
calculations and data is observed in inclusive event observables, such as the scalar sum of the p_{T} of all objects in the final-state ($\mathrm{H_T}$) above 350 GeV. Such a deviation is also seen in Z+jets events and is consistent with the observation that the mean jet multiplicity of events increases above two at about 300 GeV. Event observables, like $\mathrm{H_T}$, are better modelled using exclusive n-jets sums of fixed order pQCD calculations.

4.2 W plus heavy flavour jets

The study of the properties of a vector boson accompanied by heavy flavour jets probes the production mechanism of heavy flavour quarks, e.g. by initial state (heavy flavour quark within the proton) or by gluon splitting (e.g. $g \to b\bar{b}$). In addition it can shed light on the competing schemes for heavy quark production, e.g. different flavour (4FNS, 5FNS) and massive/massless approximations, and help understand an important background to Higgs boson analyses (e.g. WH, ZH), single top quark measurements and searches of new particles beyond the SM.

The ATLAS measurement [25] with 2011 data (4.6 fb^{-1} integrated luminosity) of W boson production in association with b-quark jets is compared to NLO predictions from POWHEG [23][24] and MCFM and LO ALPGEN predictions scaled to NNLO. The MCFM prediction is corrected for hadronisation, the POWHEG and MCFM predictions are corrected for double parton interactions, which is an important contribution to the cross section in the low jet p_{T} region (about 25%). The experimental results are observed to be above predictions as shown in fig. 4(a). Cross sections have also been measured differentially in jet p_{T}, and with and without subtraction of the single top quark contribution.

As discussed in section 2, the ATLAS W and Z inclusive measurements along with HERA data have bolstered the case for an SU(3) symmetric sea at $x \approx 0.01$. The cross section measurement



(a) (b)

Figure 4: (a) Measurements of the fiducial cross sections for W+b production for exactly 1-jet, 2-jets and 1- or 2-jets [25]. (b) Sum of cross sections for the production of $W^{\pm}\mathrm{D}^{\mp}$ and $W^{\pm}\mathrm{D}^{*\mp}$ compared to aMC@NLO predictions calculated using a range of PDF sets [26].

of W bosons in association with D mesons can also be used to constrain the s-quark PDF in the same region of x. This analysis is carried out using 4.6 fb^{-1} [26]. The charge correlation between the lepton from the W and the $\mathrm{D}^{(*)}$ is used to extract the single-charm component. Distributions are formed for both opposite charge (OS) and same charge (SS) distributions and the OS-SS combination is used for the extraction of the cross section. The yield is found by fitting the $\mathrm{D}^{\pm}$ mass (for $\mathrm{D}^{\pm}$) or the D^{*} - D^{0} mass difference (for $\mathrm{D}^{*\pm}$). The sum of cross sections for $W^{\pm}\mathrm{D}^{\mp}$ and $W^{\pm}\mathrm{D}^{*\mp}$ is shown in fig. 4(b) and it is compared to predictions from aMC@NLO [27] using six different PDF sets: CT10 [28], MSTW2008, NNPDF2.3 [29], HERAPDF1.5 which all have suppressed strangeness[2], epWZ with strangeness equal to $\bar{u}$ and $\bar{d}$ (see sec. 2), and NNPDF2.3coll [29] which includes only collider data and has an even more enhanced strange-quark contribution than epWZ. It is observed that the measurement is most consistent with predictions using epWZ and NNPDF2.3coll, both of which have enhanced strangeness as compared to the other PDFs.

5. Conclusions

The analyses presented here cover a range of measurements of W and Z production at ATLAS in pp collisions at $\sqrt{s}$ = 7 TeV. The inclusive $W^{\pm}$ and Z cross section measurements are used to determine the strange quark density at small x which is found consistent with no suppression of the $\bar{s}$ PDF relative to $\bar{d}$.

The normalised differential cross section of Z production as a function of ϕ^{*}_{η} is measured with small experimental uncertainties, probing similar physics as Z p_{T}. The predictions are largely in agreement with the experimental results within the large theoretical uncertainties.

ATLAS has also carried out a wide range of measurements of vector boson with accompanying jet production to test and constrain pQCD calculations. Scaling properties have been tested with W, Z boson plus inclusive jet production, while heavy-flavour production schemes in predictions have been tested with W, Z boson plus b-tagged jets. In many regions of phase space such measurements have experimental uncertainties which are competitive with or smaller than theoretical

[2]although in CT10 the strange contribution is less suppressed then in the others.

uncertainties. The exclusive measurement of $W^{\pm}$+$\mathrm{D}^{(*)\mp}$ cross sections has been used to extract information on the *s*-quark PDF, confirming the preference of the ATLAS data for PDFs with an SU(3) symmetric sea.

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