Measurements of W/Z production with the ATLAS detector

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Abstract. W and Z boson production have been measured in the electron, muon and tau decay channels at the LHC with the ATLAS detector. Total and differential cross sections, defined in terms of the decay lepton kinematics, have been measured as a function of rapidity and transverse momentum. Ratios of the cross sections demonstrate sensitivity to lepton universality. The kinematic distributions constrain parton densities and QCD calculations, including resummations of soft gluon radiation and the matching of NLO matrix elements (or high multiplicity tree-level matrix elements) to parton shower approximations. The polarization of W bosons is also measured, as, for the first time, is the polarization of the tau lepton in $W \rightarrow \tau \nu$ decays.

Keywords: LHC, ATLAS, W boson, Z boson, τ lepton, differential cross sections, polarizations, parton density function

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INTRODUCTION

The LHC [1] and the ATLAS [2] experiment were build for uncovering so far unseen phenomena of nature. Precision electroweak measurements play a vital role in understanding physics at the electroweak symmetry breaking scale and understanding electroweak symmetry breaking itself. Results described in this note are based on data collected with the ATLAS experiment at the LHC in 2010 (up to 35 pb^{-1}) and 2011 (up to 5 fb^{-1}), both at a proton–proton center-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$.

About one million $Z \rightarrow ll^1$ and ten million $W \rightarrow l\nu$ ($l = e, \mu$) events are produced per fb^{-1} at the LHC. The W and Z bosons are theoretically well understood and these events provide a unique and clean experimental signature. The production cross sections σ_{pp} at momentum transfer Q factorize at the common scale² μ of the boson masses (m_W, m_Z) on the generic parton distribution functions (PDF_i) of the proton as

$$\sigma_{\text{pp}}(Q) = \sum_{ij} \hat{\sigma}_{ij}(Q/\mu, \alpha_s(\mu)) \otimes \text{PDF}_i(\mu) \otimes \text{PDF}_j(\mu), \quad (1)$$

where the indices i and j run over all partons inside the proton, $\hat{\sigma}_{ij}$ is the partonic production cross section, and α_s is the strong coupling parameter. The boson rapidity

¹ Throughout this note, Z includes also the contribution due to the γ^* and interference terms.

² The renormalization scale μ_R and factorization scale μ_F are taken to be equal and both denoted by μ .

$y_{W,Z}$ and the momentum fraction of the two incoming partons are related via

$$x_{1,2} = \frac{m_{W,Z}}{\sqrt{s}} e^{\pm y_{W,Z}}. \quad (2)$$

Thus, precise measurements of differential W and Z boson production cross sections can be used to constrain PDFs in the approximate range $10^{-3} < x < 0.1$ and a Q^2 near the W and Z boson masses.

Comparing measured distributions with theoretical predictions will lead to a better understanding of these important processes in the LHC environment. Due to the copious production W and Z bosons, other observables can be measured with high precision, *e.g.*, the polarization of the τ lepton as well as the polarization of the W boson itself.

INCLUSIVE CROSS SECTIONS

ATLAS has measured the inclusive cross sections of $pp \rightarrow W \rightarrow l\nu$ and $pp \rightarrow Z \rightarrow ll$ (defined in the region $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$), where $l = e, \mu$, with 35 pb^{-1} of data collected in 2010 [3]. All correlations between different decay channels have been taken into account. The results are in good agreement with theoretical predictions at next-to-next-to leading order (NNLO) in perturbation theory and are summarized in Fig. 1.

FIGURE 1. The measured total cross sections times branching fractions for W and Z bosons [4] are compared to the theoretical predictions based on NNLO QCD calculations using the MSTW 2008 PDF set. Results are shown for the combined electron and muon decay modes.

Fiducial cross sections $\sigma_{W,Z}^{\text{fid}}$ have been defined in order to avoid theory uncertainties from phase-space extrapolations from the measured lepton kinematic range to their full range. In addition, ratio measurements have better precision due to (partial) cancellation of systematic uncertainties. The ratio $\sigma_{W^\pm}^{\text{fid}}/\sigma_Z^{\text{fid}}$ has been measured as $10.703 \pm 0.078(\text{stat}) \pm 0.110(\text{syst}) \pm 0.008(\text{acc})$, where acc represents the uncertainty on the kinematic and geometric acceptance, in good agreement with several tested PDFs.

In order to test lepton universality, *i.e.*, the universal coupling of W or Z bosons to all charged leptons, the ratios $R_W = \sigma_W \cdot \text{Br}(W \rightarrow e\nu) / (\sigma_W \cdot \text{Br}(W \rightarrow \mu\nu))$ and $R_Z = \sigma_Z \cdot \text{Br}(Z \rightarrow ee) / (\sigma_Z \cdot \text{Br}(Z \rightarrow \mu\mu))$ have been measured in a common fiducial region for

the electron and muon channels. The results $R_W = 1.006 \pm 0.024$ and $R_Z = 1.018 \pm 0.031$ are in good agreement with the current world average and theory expectations.

Measurements have also been performed with τ leptons in the final state. The total W production cross section times the branching fraction to $\tau\nu$ is measured in the hadronic τ decay channels with 34 pb^{-1} data collected in 2010 as $11.1 \pm 0.3 \text{ (stat)} \pm 1.7 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ nb}$ [5] and is in good agreement with the other leptonic channels mentioned above and with theory predictions. The corresponding $Z \rightarrow \tau\tau$ total cross section has been measured with a data sample collected during 2011, corresponding to an integrated luminosity of $1.34\text{--}1.55 \text{ fb}^{-1}$, depending on the final state, [6]. Three decay topologies have been used, muonic plus hadronic, electronic plus hadronic, and electronic plus muonic. The measured cross section time branching fraction $0.92 \pm 0.02 \text{ (stat)} \pm 0.08 \text{ (syst)} \pm 0.03 \text{ (lumi)} \text{ nb}$ [6] is in agreement with the other leptonic boson decay channels and theory predictions.

DIFFERENTIAL CROSS SECTIONS

The production cross sections of W and Z bosons can also be measured as a function of the transverse momentum of the boson. At low p_T , effects of soft and collinear parton emission and the validity of logarithmic resummation up to next-to-next-to-leading logarithm (NNLL) can be tested while emissions of high- p_T partons affect the distribution at high p_T . These measurements were performed with up to 40 pb^{-1} of 2010 data and the measured distributions in the electron and muon decay channel were unfolded and combined to obtain differential cross sections normalized to unit area as a function of the W p_T [7] and Z p_T [8]. The resulting distributions are compared to several perturbative QCD (pQCD) calculations and event generators. Generally, the fixed-order pQCD calculations at $O(\alpha_s^2)$ agree better with the measurement compared to the $O(\alpha_s)$ calculation, but still, the effect of missing higher orders is notable.

FIGURE 2. Differential cross section measurement for leptonic decays for (left) Z bosons versus its rapidity, (middle) W^+ and (right) W^- bosons versus the charged lepton pseudorapidity compared to NNLO theory predictions using various PDF sets. The ratio of theoretical predictions to data is also shown. Theoretical points are displaced for clarity within each bin [3].

The production cross sections of the Z boson as a function of the boson rapidity (y_Z) and those of the W boson as a function of the charged-lepton pseudo-rapidity (η_l) have

been measured with 33 pb^{-1} and 36 pb^{-1} of 2010 data in the electron and muon channel, respectively [3]. The measured distributions, a combination of the electron and muon decay channels, agree well with several PDFs, as can be seen in Fig. 2, however, some disagreement between data and some PDF sets is visible in certain regions.

These measurements can in turn be used to constrain PDFs due to the relationship between the parton x and the boson rapidity, as expressed in Eq. 2. Especially the strange-quark density is of interest as it is thus far poorly known. Flavor $SU(3)$ symmetry suggests equal densities of the u , d , and s sea quarks. However, due to the larger strange-quark mass, this is not an exact symmetry and generally, many PDFs assume a suppression of the strange quark density. Specifically, the ratio $r_s = (s(x) + \bar{s}(x)) / 2\bar{d}(x)$ is often assumed to be 0.5. However, the ATLAS combined PDF-fit analysis of HERA I ep data and ATLAS W and Z data allows for a determination of r_s by allowing the strange-quark density to be determined by the fit. This results in $r_s = 1.00^{+0.09}_{-0.10}$ at a momentum transfer $Q^2 = m_Z^2$ and a parton $x = 0.013$ [9]. It improves the agreement with the W and Z cross section measurements, as can be seen in Fig. 3(a).

FIGURE 3. (a) Measured and predicted fiducial cross section ratios $(W^+ + W^-)/Z$ determined in a common kinematic and geometric acceptance region for the electron and muon channels; the blue star is the result of the fit described in the QCD analysis paper on the strange density [9]. (b) Simulated signal and background templates for left and right-handed tau decays along with the observed charged asymmetry distribution in data. The best fit resulting from maximizing the likelihood is plotted in bold [10].

Another quantity of interest is the W charge asymmetry as a function of the pseudorapidity of the charged decay lepton, defined as $A(\eta_l) = \frac{d\sigma_{W^+}/d\eta_l - d\sigma_{W^-}/d\eta_l}{d\sigma_{W^+}/d\eta_l + d\sigma_{W^-}/d\eta_l}$. This distribution has been measured with 33 pb^{-1} and 36 pb^{-1} of 2010 data in the electron and muon channel, respectively, combining both channels [3]. The agreement with several different PDF sets is good, however some small distinctions amongst data and the different PDF sets can be seen in the shape of the distribution.

POLARIZATIONS

ATLAS has measured for the first time the polarization of τ leptons in W boson decays with 24 pb^{-1} of 2010 data [10]. The τ polarization is defined as $P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$ where σ_R (σ_L) is the cross section for right(left)-handed τ^- production. It is known

that parity is violated in τ decays and that the decay product kinematics carry information about the τ helicity. P_τ is expected to be -1 in W decays and 0 in Standard Model Higgs boson decays. In decays of the type $\tau^- \rightarrow \rho^- \nu$, $\rho^- \rightarrow \pi^- \pi^0$ a discriminating variable $\Upsilon = (E_T^{\pi^-} - E_T^{\pi^0})/|\vec{p}_T^{\pi^-} + \vec{p}_T^{\pi^0}|$ can be determined. Its distribution for left-handed and right-handed τ can be seen in Fig. 3(b), together with the resulting data points. The τ polarization is determined from a fit to this distribution as $P_\tau = -1.06 \pm 0.04(\text{stat})_{-0.07}^{+0.05}(\text{syst})$, in agreement with theoretical expectation.

The polarization of the W boson has also been measured with 35 pb^{-1} of 2010 data in the electron and muon decay channel [11]. W bosons are produced at the LHC at leading order via $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$. In the massless quark limit, the quark (anti-quark) is purely left-handed (right-handed) and the quarks carry generally a larger momentum than the anti-quarks. Thus, W bosons with large rapidity are predominantly left-handed. At large W p_T , gluons are participating in the production of the W boson and due to its vector nature, the simple argument for the W polarization no longer applies. Thus, the measurement of the W boson polarization has been performed in two bins: $35 \text{ GeV} < p_T(W) < 50 \text{ GeV}$ and $p_T(W) > 50 \text{ GeV}$. The difference between the left-handed and right-handed polarization has been measured in order to reduce systematic uncertainties. The results for $p_T(W) > 50 \text{ GeV}$ are $f_L - f_R = 0.252 \pm 0.017(\text{stat}) \pm 0.030(\text{syst})$ and for the transverse polarization component $f_0 = 0.127 \pm 0.30(\text{stat}) \pm 0.108(\text{syst})$.

SUMMARY

The ATLAS collaboration has performed many impressive measurements in events with a produced W or Z boson. The precisely measured total cross-sections agree well with theoretical predictions. Differential cross-section measurements have for the first time been used to constrain the strange-quark density inside the proton and polarization measurements of the W boson and the τ lepton in W boson decays are found to be in agreement with theoretical expectations.

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