PROCEEDINGS OF SCIENCE

Production of $W^{\pm}$ bosons in *pp* collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector

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Precision measurements of electroweak boson production in *pp* collisions are considered benchmark tests of the Standard Model. In particular, they provide verification for predictions of the electroweak theory and quantum chromodynamics (QCD). The rapidity of electroweak bosons produced in *pp* collisions is strongly correlated with the initial quark dynamics. Therefore, these measurements can provide constraints on parton distribution functions (PDFs) of the proton. This study presents the first measurement of W boson production in *pp* collisions at $\sqrt{s} = 5.02$ TeV using data collected by the ATLAS experiment in 2015. Fiducial cross-sections for W^{+} and W^{-} boson production are measured in leptonic decay channels. The cross-sections are measured inclusively and differentially in the decay lepton pseudorapidity. In addition, a measurement of the lepton charge asymmetry is presented. The measured cross-sections and charge asymmetry are compared to predictions calculated at next-to-next-to-leading order in QCD using several recent sets of PDFs.

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1. Introduction

At hadron colliders, one can use measurements of W boson production to probe precisely the electroweak sector of the Standard Model. These measurements provide also information about the structure of hadrons, which is governed by quantum chromodynamics (QCD) in the non-perturbative regime. The dominant production modes of W bosons in proton–proton (pp) collisions at the Large Hadron Collider (LHC) involve interactions of a valence quark and an antiquark from the sea ($u\bar{d} \to W^+$ and $d\bar{u} \to W^-$). Through the close correlation between the W boson rapidity and the momentum fractions of the proton carried by the (anti)quark, it is possible to use measurements of W boson production to constrain parton distribution functions (PDFs) of the proton. In particular, measurements differential in rapidity can differentiate between different models of the proton structure.

This report presents a measurement of W boson production based on data from 25 pb^{-1} of pp collisions at $\sqrt{s} = 5.02$ TeV [1], which was collected by the ATLAS experiment [2] in 2015. The measurement uses leptonic decay channels ($W^\pm \to \ell^\pm \nu$, $\ell = e,\ \mu$), and provides integrated cross-sections as well as cross-sections measured differentially in the pseudorapidity of the decay lepton. In addition, the lepton charge asymmetry is extracted from the measured differential cross-sections.

2. Measurement procedure

Integrated and differential cross-sections for W boson production are measured in a fiducial phase-space region with requirements applied to the lepton transverse momentum, p_{T}^{ℓ}, the lepton pseudorapidity, η_ℓ, the neutrino transverse momentum, p_{T}^{ν}, and the lepton–neutrino transverse mass, m_{T}:

$$p_{\mathrm{T}}^{\ell} > 25\ \text{GeV}, \quad |\eta_\ell| < 2.5, \quad p_{\mathrm{T}}^{\nu} > 25\ \text{GeV}, \quad m_{\mathrm{T}} > 40\ \text{GeV}. \tag{2.1}$$

These requirements are mainly driven by the acceptance of the ATLAS detector and kinematics of W boson decay products. The transverse mass is defined as:

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos\Delta\phi_{\ell,\nu})}, \tag{2.2}$$

where $\Delta\phi_{\ell,\nu}$ is the azimuthal angle between the lepton and the neutrino directions.

The cross-sections are calculated using the formula:

$$\sigma^{\mathrm{fid}}_{W^\pm \to \ell^\pm \nu} = \frac{N_{\mathrm{sel}} - N_{\mathrm{bkg}}}{C_W \cdot L_{\mathrm{int}}}, \tag{2.3}$$

where N_{sel} and N_{bkg} are the number of selected events and the estimated number of background events, respectively. Correction factors C_W account for the event selection efficiency. The integrated luminosity of the dataset is denoted by L_{int}. For the calculation of differential cross-sections in intervals of $|\eta_\ell|$, $\mathrm{d}\sigma_{W^\pm}/\mathrm{d}|\eta_\ell|$, the above expression is evaluated for events falling into a given interval and divided by the width of this interval.

The lepton charge asymmetry is evaluated from the measured differential cross-sections as follows:

$$A_\ell(|\eta_\ell|) = \frac{\mathrm{d}\sigma_{W^+}/\mathrm{d}|\eta_\ell| - \mathrm{d}\sigma_{W^-}/\mathrm{d}|\eta_\ell|}{\mathrm{d}\sigma_{W^+}/\mathrm{d}|\eta_\ell| + \mathrm{d}\sigma_{W^-}/\mathrm{d}|\eta_\ell|}. \tag{2.4}$$

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3. Data analysis

Candidate events for W boson production are selected with single-lepton triggers, which require electrons (muons) to have a p_{T} above 15 GeV (14 GeV). Reconstructed electrons are required to pass a kinematic selection of $p_{\mathrm{T}}^{e} > 25$ GeV and $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, while the kinematic requirements for muons are $p_{\mathrm{T}}^{\mu} > 25$ GeV and $|\eta_\mu| < 2.4$. The amount of events from background processes is reduced by requiring the leptons to pass criteria related to identification and isolation. In order to suppress the background contributions from $Z \to \ell^+\ell^-$ decays, only events with exactly one high-quality lepton (matched to the trigger) are accepted in the analysis. Neutrinos produced in leptonic W boson decays escape the interaction region without being detected. However, their kinematics in the transverse plane can be inferred from a global momentum imbalance. In this measurement, the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, is calculated from the hadronic recoil reconstructed using a particle flow algorithm [3]. Requirements on the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and on the detector-level transverse mass, $m_{\mathrm{T}} > 40$ GeV, are used to effectively reject multi-jet background events.

Theoretical predictions for W boson production cross-sections have reached a few-percent precision. In order for the measurements to match the precision of predictions, it is necessary to carry out dedicated studies of the detector performance for the reconstruction of leptons and the hadronic recoil. An example of such studies for the $\sqrt{s} = 5.02$ TeV dataset is presented in Figure 1, which shows efficiencies for the reconstruction, identification, isolation and trigger criteria of single electron and muon candidates. These efficiencies are measured with the tag-and-probe method in $Z \to \ell^+\ell^-$ events. Electron efficiencies vary with η_e between 85% and almost 100%, with the efficiencies in the forward detector regions being typically lower than in the central region. For muons, the reconstruction/identification and isolation efficiencies are above 95% almost in the full η_μ range. The muon trigger efficiency is about 90% in the forward detector regions and varies between 60% and 85% in the central region, which is related to the different acceptance of trigger systems installed in the two regions.

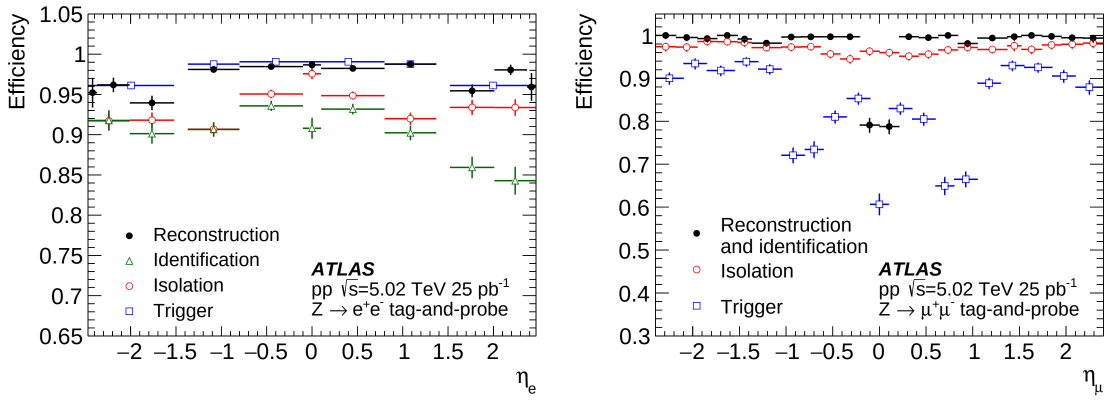

Figure 1: Efficiencies of reconstruction, identification, isolation and trigger requirements as a function of lepton pseudorapidity for electrons (left) and muons (right) measured using the tag-and-probe method [1]. The efficiency of each selection is defined with respect to leptons selected in the previous step.

The background estimation relies both on Monte Carlo (MC) simulations of selected processes and on the data itself. Background contributions from single electroweak boson processes ($Z \to \ell^+\ell^-$, $W^\pm \to \tau^\pm\nu$, $Z \to \tau^+\tau^-$), top-quark production ($t\bar{t}$, Wt) and diboson production (WW, WZ, ZZ) are evaluated using samples of simulated events. The simulated events are required to pass the event selection and the remaining counts are normalised to the luminosity of the data. The contributions from multi-jet background processes are estimated using a data-driven approach. In this procedure, template fits are made to the distributions of several kinematic variables: p_{T}^{ℓ}, $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{T}. Examples of $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions after fits are shown in Figure 2. The templates for the signal process as well as for electroweak and top-quark background processes are taken from the MC simulation, while the templates for the multi-jet background are taken from events with non-isolated leptons in data. In total, background processes contribute a few percent to the number of selected events. The largest contribution in the electron channels comes from $W^\pm \to \tau^\pm\nu$ decays (1.8%) and from multi-jet production (0.9–1.4%). In the muon channels, the dominant background process is $Z \to \mu^+\mu^-$ production (2.8–3.8%), while the multi-jet background contribution (0.1–0.2%) is much smaller than in the electron channels.

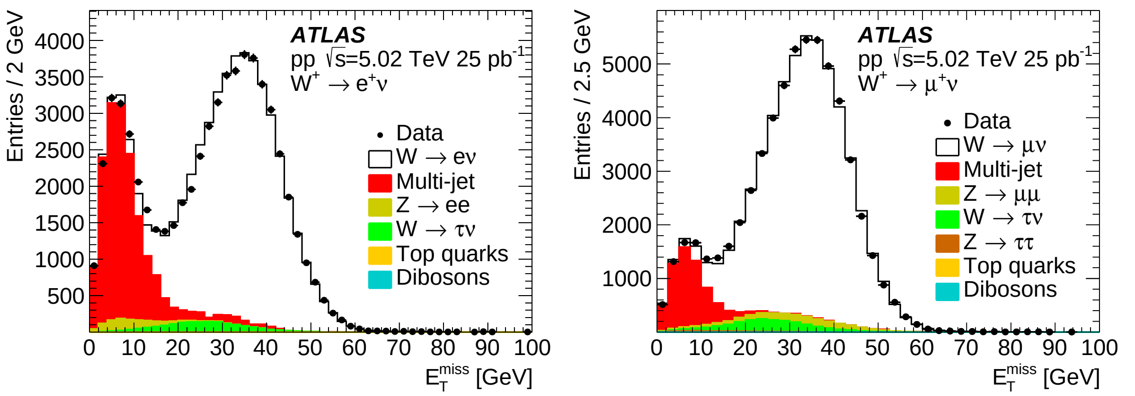

Figure 2: Distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$ used to extract multi-jet yields in the electron (left) and muon (right) channels after performing the template fits [1]. Only the statistical uncertainties of the data are shown.

4. Results

The cross-sections for W boson production measured separately in the electron and muon decay channels are found to be compatible. Therefore, they are combined using the Best Linear Unbiased Estimate method [4], which takes into account uncertainty correlations. After combination, the integrated cross-sections for W^+ and W^- boson production are found to be:

$$\sigma^{\mathrm{fid}}_{W^+\to\ell^+\nu} = 2266 \pm 9 \text{ (stat)} \pm 29 \text{ (syst)} \pm 43 \text{ (lumi) pb}, \quad (4.1)$$

$$\sigma^{\mathrm{fid}}_{W^-\to\ell^-\nu} = 1401 \pm 7 \text{ (stat)} \pm 18 \text{ (syst)} \pm 27 \text{ (lumi) pb}, \quad (4.2)$$

where “stat”, “syst” and “lumi” denote the statistical, systematic and luminosity uncertainties, respectively. The total uncertainties in the measured cross-sections are at the level of 2.3–2.4%, or 1.3–1.4% if the luminosity uncertainty is omitted.

Combined differential cross-sections for W boson production are presented in Figure 3. The total measurement uncertainties vary between 2.9% and 4.0%. The data are compared to several theoretical predictions obtained with different modern PDF sets: CT14 NNLO [5], NNPDF3.1 [6], MMHT2014 [7], HERAPDF2.0 [8] and ABMP16 [9]. An optimised version of the DYNNLO 1.5 program [10, 11] is used for the calculation of the predictions. The best agreement with the measured cross-sections is achieved with the NNPDF3.1 PDF set, which was derived from high-precision LHC measurements of electroweak boson production at $\sqrt{s} = 7$ and 8 TeV, e.g. those described in Refs. [12–15]. Other calculations predict cross-sections which are lower by a few percent than those measured.

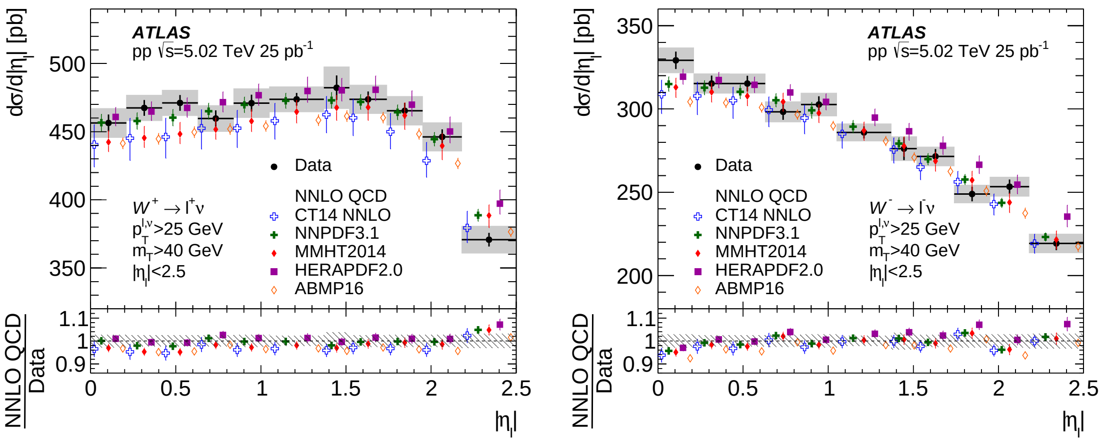

Figure 3: Differential cross-sections for W^+ (left) and W^- boson (right) production as a function of absolute decay lepton pseudorapidity compared with theoretical predictions [1]. Statistical and systematic uncertainties are shown as corresponding bars and shaded bands on the data points. The luminosity uncertainty is not included. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.

The lepton charge asymmetry extracted from the differential cross-section measurements is presented in Figure 4. This observable has the advantage that most systematic uncertainties cancel out, so that the total uncertainty is dominated by the statistical component. As a result, the absolute uncertainties in the measured lepton charge asymmetry are typically at the level of $1 \cdot 10^{-3}$. Nevertheless, this measurement is not able to differentiate strongly between the various PDF sets, since all of them predict a similar lepton charge asymmetry.

5. Summary

A measurement of integrated and differential fiducial cross-sections for W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV has been presented. The precision of the measurement reaches 2.3–2.4% for the integrated cross-sections, while the total uncertainty in the differential cross-sections varies between 2.9% and 4.0%. The typical uncertainty in the lepton charge asymmetry is at the level of $1 \cdot 10^{-3}$.

The differential cross-section measurements are best described by next-to-next-to-leading-order QCD predictions calculated using the NNPDF3.1 PDF set, while predictions based on other modern PDF sets tend to underestimate the data by a few percent. All predictions for the lep-

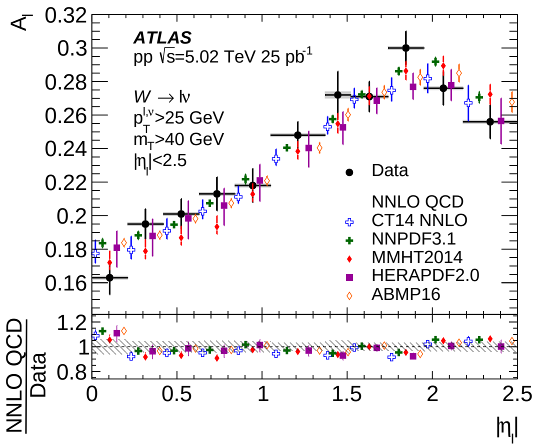

Figure 4: Lepton charge asymmetry for W bosons as a function of absolute decay lepton pseudorapidity compared with theoretical predictions [1]. Statistical and systematic uncertainties are shown as corresponding bars and shaded bands on the data points. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.

ton charge asymmetry agree with the data, so that the current measurement of the asymmetry has limited power to discriminate between the PDF sets.

The presented results provide also an important reference for the measurement of W boson production in lead–lead collisions at the same centre-of-mass energy [16].

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