Measurement of the W and Z boson cross section at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

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This article reports the measurement of the $W^{\pm}$ and Z boson cross sections, their ratios and the ratio of the $t\bar{t}$ and W boson fiducial cross sections, using proton-proton collision data obtained at the new centre-of-mass energy of $\sqrt{s} = 13.6$ TeV by the ATLAS experiment at the Large Hadron Collider. The data used in this measurement correspond to an integrated luminosity of 29 fb^{-1} and was collected in 2022. The large cross sections of these processes, together with clean experimental signatures achieved through their leptonic decays, allow an excellent experimental precision reaching the percent level, and in the case of the cross-section ratios, the sub-percent level. Finally, these results are compared with state-of-the-art Standard Model theoretical predictions using several different PDF sets.

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1 Introduction

Measurements of the W and Z boson cross section provide important tests of the Standard Model (SM), offering insights into the underlying dynamics of strongly interacting particles and proton structure. Several measurements at different centre-of-mass energies have been performed in the past, providing stringent tests of theoretical predictions, especially as the experimental precision of these measurements has reached percent level, and even sub-percent level in the case of cross-section ratios.

In this article, measurements of the cross sections of the W and Z bosons and their ratios at $\sqrt{s} = 13.6$ TeV are presented, in addition to the fiducial cross section ratios of $t\bar{t}$ production relative to W boson production [1]. This measurement uses proton-proton collision data recorded by the ATLAS experiment [2,3] during 2022, corresponding to an integrated luminosity of 29 fb^{-1}. The large W and Z boson production cross sections, coupled with clean experimental signatures through their leptonic decays, offer the ideal testing ground for early validation of the detector performance at the start of the Run-3 data-taking period at ATLAS, and for validating Standard Model predictions at the new centre-of-mass energy.

2 Analysis overview

Single electron and muon triggers are used to select events, followed by an offline selection where leptons are required to have transverse momentum $p_{\mathrm{T}} > 27$ GeV and be isolated from hadronic activity. For the Z boson selection, events are required to have two opposite sign, same-flavour leptons, where the invariant mass of the dilepton pair is required to be in the range

$66 < m_{\ell\ell} < 116$ GeV. For the W boson selection, events are required to have only one lepton, with missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and a transverse mass $m_{\mathrm{T}}^{\mathrm{W}} > 50$ GeV.

Background contributions to the W and Z boson channels correspond to two categories: electroweak (including single-boson and diboson production) and top-quark processes, which are estimated using simulation, and the multi-jet background, estimated using a data-driven technique and summarised in the next section. Figure 1 shows the $m_{\mathrm{T}}^{\mathrm{W}}$ and the invariant mass of the lepton pair, $m_{\ell\ell}$, distributions in the $W^+ \to e^+\nu$ and $Z \to \mu^+\mu^-$ channels respectively. In this Figure, the data and signal simulations are included, together with the simulations of the background processes; the systematic uncertainties are also included. A complete description of the uncertainties considered in this measurement are described in detail in Ref. [1].

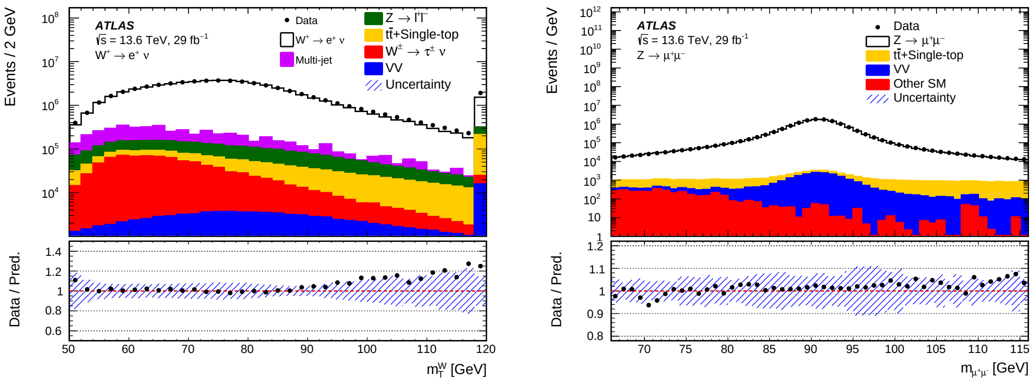

Figure 1 – The measured $m_{\mathrm{T}}^{\mathrm{W}}$ distribution (dots) in the $W^+ \to e^+\nu$ (left) and the measured $m_{\ell\ell}$ distribution (dots) in the $Z \to \mu^+\mu^-$ channel (right). The predictions for the signal and background processes are also included. The hatched bands represent the uncertainties. [1].

The fiducial cross sections are extracted with binned profile likelihood fits [4]. The Z boson cross sections are obtained through individual fits to two same-flavour dilepton regions (e^+e^- and $\mu^+\mu^-$), while the W boson cross sections and fiducial ratios are obtained through fits using four single-lepton ($e^-\bar{\nu}$, $e^+\nu$, $\mu^-\bar{\nu}$ and $\mu^+\nu$) and the two same-flavour dilepton regions. The $t\bar{t}$ to W-boson cross-section ratios are derived in separate fits to the four single-lepton, the two same-flavour dilepton and two $t\bar{t}$ $e\mu$ regions. The inputs for the $t\bar{t}$ regions are obtained from Ref. [5], where a complete description of the event selection for these can be found. Total cross sections σ^{tot} are also obtained by dividing the fiducial cross section σ^{fid} by the detector acceptance A.

3 Data-driven background estimation

The multi-jet (MJ) contribution in the W boson channels is obtained by performing profile likelihood fits using templates derived from control regions, defined by requiring leptons to fail the isolation requirements. Several MJ templates are created by further dividing the control regions into several isolation slices, as illustrated in Figure 2 (left). The normalisation of the MJ contribution is extracted in each of the four W channels, using MJ templates from four isolation slices and two discriminating variables ($E_{\mathrm{T}}^{\mathrm{miss}}$ and $m_{\mathrm{T}}^{\mathrm{W}}$). Finally, to reduce the bias due to the choice of the lepton isolation working point used to obtain the MJ templates, an extrapolation is performed in the track isolation. The final value for the MJ yield in the signal region is obtained from a quadratic fit and the difference between the linear and quadratic fits is assigned as an additional uncertainty. The track isolation extrapolation for the $W^+ \to e^+\nu$ channel is illustrated in Figure 2 (right), where the value obtained for the MJ fraction in the signal region is shown, together with the uncertainty due to the quadratic fit, and the uncertainty due to the difference between the quadratic and the linear fit.

In the Z boson channels, the MJ contribution is obtained from the number of charge misidentified leptons and is found to be negligible, so it is not considered in the analysis.

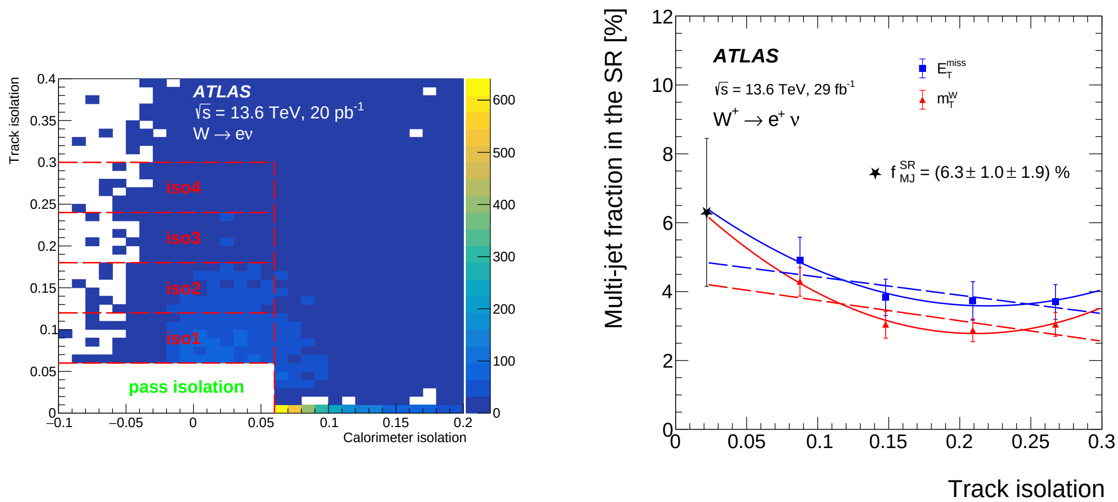

Figure 2 – Track isolation slices used to extract the multi-jet background for the electron channels (left) and track isolation extrapolation of the multi-jet fraction in the signal region (SR) for the $W^+ \to e^+\nu$ channel (right) [1].

4 Results

Theoretical predictions calculated at next-to-next-to-leading-order (NNLO) plus next-to-next-to-leading-logarithmic (NNLL) QCD and next-to-leading-order (NLO) electroweak (EW) accuracy, using different PDF sets, are compared to the measured fiducial cross sections and their ratios. Figure 3 shows the results for the W^-, W^+ and Z fiducial cross sections (top), the cross-section ratios R_{W^+/W^-} (bottom left), $R_{W^\pm/Z}$ (bottom centre) and $R_{t\bar{t}/W^\pm}$ (bottom right). For the fiducial cross section measurements, the total uncertainty with and without the contribution from the luminosity uncertainty is illustrated, while for the ratios only the total uncertainty is illustrated as the luminosity and other sources of uncertainties such as lepton efficiencies are cancelled in the ratios. The dominant sources of uncertainties for the fiducial cross sections include luminosity, jet-related and MJ background uncertainties for the W boson, and luminosity and lepton efficiency for the Z boson measurement. For the R_{W^+/W^-} ratio, the MJ uncertainties dominate as these are uncorrelated between channels, while for the $R_{W^\pm/Z}$ ratio the jet-related uncertainties are the largest. For $R_{t\bar{t}/W^\pm}$, the largest contributions to the uncertainty are the $t\bar{t}$ modelling, the jet-related and MJ uncertainties.

Overall, good agreement is observed between the results and predictions for the W and Z boson results, while the $t\bar{t}/W^\pm$ ratio measurements are slightly underestimated by the predictions.

The NNLO theoretical predictions are compared in Figure 4 to the $W^\pm$ and Z total cross sections from the measurements presented here and from other measurements at several centre-of-mass energies. Good agreement is also observed between data and predictions.

5 Summary

Measurements of the W and Z vector boson production cross sections and their ratios are presented using proton-proton collision data collected by the ATLAS experiment at a centre-of-mass energy $\sqrt{s} = 13.6$ TeV, corresponding to an integrated luminosity of 29 fb^{-1}. Overall, good agreement between the data and theoretical predictions is observed; the measured $t\bar{t}/W$ ratio has a tendency to be underestimated by the prediction.

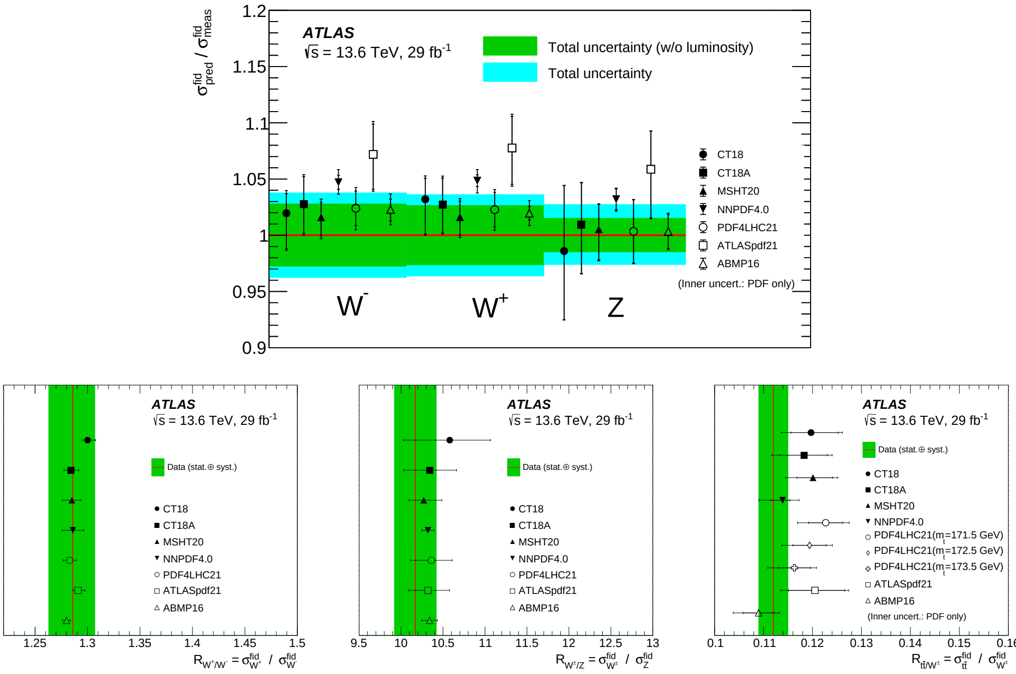

Figure 3 – The ratio of the predictions obtained with different PDF sets and the measured fiducial cross sections for W^{-}, W^{+} and Z bosons (top), and their ratios $R_{W+/W-}$ (bottom left) and $R_{W\pm/Z}$ (bottom centre), and the ratio of $t\bar{t}$ over the W-boson fiducial cross sections, $R_{t\bar{t}/W\pm}$ (bottom right). The outer (inner) band in the top plot corresponds to the total uncertainty including (excluding) the luminosity uncertainty. The vertical band in the other plots shows the total (systematic and statistical) uncertainty in the data. The error bars on the predictions correspond to the theory uncertainties with the inner error bars (where available) representing the contributions from the PDF uncertainty [1].

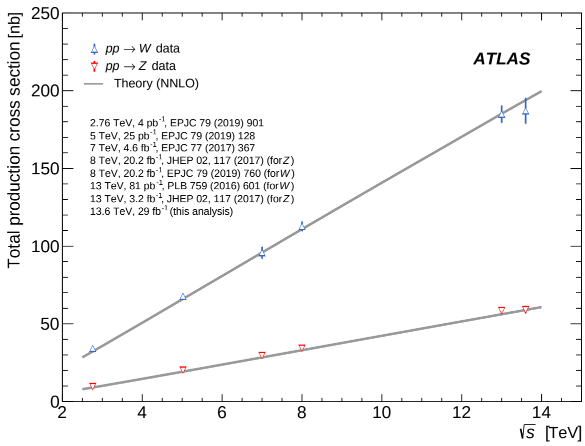

Figure 4 – The measured W and Z boson total production cross sections in the leptonic decay channel at different values of centre-of-mass energy. For comparison, the central values of the NNLO predictions based on the CT14NNLO PDF set are included [1].

References

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