PROCEEDINGS OF SCIENCE

Recent diboson and polarization measurements at ATLAS

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Diboson production in hadron-collider experiments provides access to the self-couplings governing gauge vector bosons, as anticipated by the electroweak sector of the Standard Model of particle physics. Moreover, it offers valuable information concerning proton structure. Precise measurements of differential cross-sections serve as important tests for perturbative corrections in quantum chromodynamics and the electroweak unification. The meticulous prediction of diboson processes plays also a crucial role, as they contribute to background sources in other precision measurements of the Standard Model and in quests for phenomena beyond the Standard Model. This manuscript highlights three distinct measurements of diboson processes using proton-proton collisions, conducted with the dataset recorded with the ATLAS detector at the Large Hadron Collider between 2015 and 2018 at a center-of-mass energy of $\sqrt{s}$ = 13 TeV. Precision measurements of differential cross-sections for W^+W^-, $W^\pm Z$ and $Z\gamma$+jets production, including a first observation of joint-polarization states in $W^\pm Z$ final states as well as polarization fractions of joint and individual states of massive gauge vector bosons, are presented.

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1. Introduction

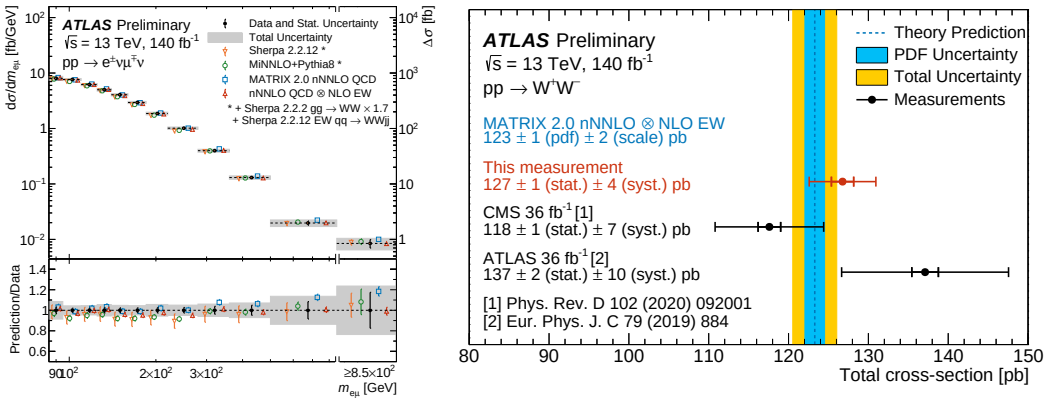
Experimental investigations of diboson processes in proton-proton (pp) collisions at the center-of-mass energies accessible at the Large Hadron Collider (LHC) [1] offer insights into gauge vector boson self-couplings predicted by the electroweak sector of the Standard Model (SM) and into the proton structure. Longitudinal polarization modes of massive gauge vector bosons resulting from electroweak symmetry breaking can also be experimentally probed. In Sections 2, 3 and 4, this manuscript highlights fiducial differential cross-section measurements of W^+W^-, $Z\gamma$ and $W^\pm Z$ production, respectively, with the ATLAS detector [2]. The later includes the first observation of joint-polarized $W^\pm Z$ final states.

2. Measurements of W^+W^- production cross sections

At hadron colliders, measurements of W-boson pair production in pp collisions are performed in the presence of large irreducible backgrounds from the production of top-quarks, dominated by $t\bar{t}$, and Drell-Yan Z+jets. For the first time, ATLAS reports fiducial integrated and differential cross-section measurements of the W^+W^- production in a fully jet-inclusive phase space, allowed by accurate data-driven estimation of the $t\bar{t}$ and lepton misidentification backgrounds [3]. Using fully leptonic decays into one electron and one muon of opposite electric-charge, Drell-Yan contributions are suppressed by requiring a dilepton invariant mass greater than 85 GeV. Top-quark contributions, comprising 48% of the overall SM prediction and 80% of the total background within the fiducial region, are mitigated by rejecting events featuring jets involving b-hadron decays (b-jets).

Contributions from $t\bar{t}$ events are estimated by an in-situ determination of both the $t\bar{t}$ effective production cross-section and the b-jet reconstruction efficiency bin by bin, using two regions with exactly 1 and 2 b-jets. Input from Monte Carlo (MC) simulations is required to infer the correlations between reconstruction of the first and the second b-jet in the event. Single-top contributions are estimated using MC simulation. Contributions from lepton misidentification are estimated after extrapolation in a control region where one of the leptons in the final state fulfills a selection criteria designed to select mostly misidentified leptons. The extrapolation factors are determined in a region enriched in misidentified leptons. Events arising from Drell-Yan Z-boson and diboson (VZ and $V\gamma$, with $V = W, Z$) production are estimated using MC simulation.

Unfolded differential distributions across twelve observables related to lepton, jet and E_T^{miss} kinematics are reported. State-of-the-art theory predictions, including perturbative corrections up to NNLO accuracy in QCD and NLO in electroweak theories, are in excellent agreement with the data. The differential cross-section as a function of the dilepton invariant mass $m_{e\mu}$ is shown in Figure 1a. A profile likelihood fit is performed in the signal region to determine the signal strength, used to obtain the integrated fiducial cross-section with a precision of 3.1%, dominated by systematic uncertainties of the $t\bar{t}$ and lepton misidentification background estimations. This corresponds to the most precise W^+W^- cross-section measurement performed in hadron collisions to date. The fiducial cross-section measurement is extrapolated to the full phase space and found to be in agreement with previous LHC measurements and SM prediction (Figure 1b).



(a) **(b)**

Figure 1: Measurements of (a) the fiducial differential W^+W^- production cross-section as a function of the dilepton invariant mass, $m_{e\mu}$, compared to state-of-the-art theory predictions derived in MiNNLO [5, 6] at NNLO accuracy in QCD, MATRIX 2.0.1 [4] at both nNNLO in QCD and nNNLO QCD⊗NLO EW and Sherpa 2.2.12 [7] at NLO in QCD, and (b) the total W^+W^- production cross-section, compared to the state-of-the-art SM prediction from MATRIX 2.0.1 at nNNLO QCD⊗NLO EW accuracy [4] as well as previous ATLAS [8] and CMS [9] measurements using the partial Run 2 dataset recorded between 2015 and 2016. Source: [3].

3. Measurements of $Z\gamma$+jets differential cross sections

Using $Z\gamma \to \ell\bar{\ell}\gamma$ final states, with $\ell = e, \mu$, precision measurements of $Z\gamma$ production in association with jets, including double-differential cross-section measurements, are reported for the first time by the ATLAS Collaboration across 13 differential observables related to the jet, lepton and photon kinematics [10]. The fiducial region targets initial-state radiation of the reconstructed photon by constraining the sum dilepton and dilepton+photon invariant masses to be at least twice the mass of the Z boson.

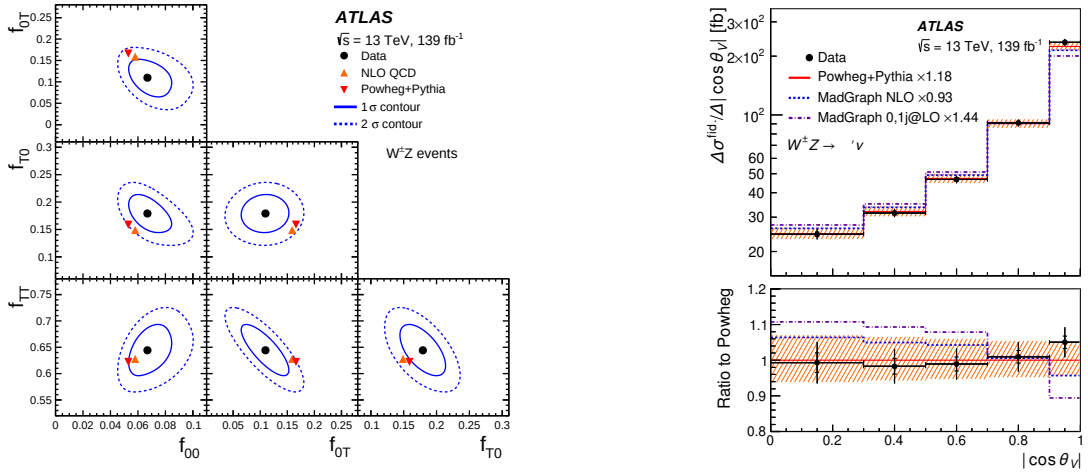
The measured integrated cross-section in the fiducial phase space is $\sigma = 534 \pm 2$ (stat) $\pm$ 13 (syst) $\pm$ 9 (lumi) fb. The results are compared to a number of MC predictions, in good agreement with the SM prediction.

4. Observation of gauge boson joint-polarization states in $W^\pm Z$ production

The ATLAS Collaboration releases the first observation of joint-polarization states of gauge massive vector bosons performed in a hadron collider using $W^\pm Z$ production in pp collisions, including also experimental determination of the polarization fractions of joint and individual states [12]. Fiducial cross-section measurements of inclusive $W^\pm Z$ production are also reported.

Joint polarization modes of the $W^\pm Z$ final states are classified using angular distributions defined in the *modified helicity reference frame*, which fixes the z-axis to the direction of the corresponding boson in the diboson center-of-mass frame [13].

The longitudinal component of the neutrino momentum, necessary to characterize of the angular distributions related to the W-boson decay in the modified helicity frame, is inferred via a neural network regression, improving the m_T resolution by 10% with respect to the previous analytical inference. At the reconstructed level, the sensitivity of the angular distributions is not sufficient to categorize the different joint polarization states. A deep neural network classifier is implemented to maximize the separation, defining a category for each joint polarization mode.



(a) (b)

Figure 2: Measurements in $W^{\pm}Z$ production of (a) joint helicity fractions of the W and Z bosons compared to fixed order theoretical predictions at NLO in QCD [13] and Powheg+Pythia [14], and (b) the fiducial differential cross-section measurement of inclusive $W^{\pm}Z$ production as a function of $|\cos\theta_V|$, compared to SM predictions from Powheg+Pythia and MadGraph5_aMC@NLO+Pythia [11]. Source: [12].

Angular observables are proven to be sensitive to higher-order corrections in the prediction of joint $W^{\pm}Z$ polarization modes [13]. The most accurate MC simulation of the independent polarization states interfaced with parton shower available, MadGraph 0,1j@LO +Pythia [11], only includes real correction up to NLO in QCD. However, full NLO fixed-order predictions of differential distributions are available at Born level. A DNN-based reweighting strategy is implemented to include effects due to virtual NLO corrections at reconstructed level on the MadGraph 0,1j@LO MC sample. Using this approach, the differential shapes closure to the folded fixed-order predictions within 10%. The joint $W^{\pm}Z$ polarization fractions f_{00}, f_{0T}, f_{T0} and f_{TT} are measured with an observed (expected) significance of 7.1σ (6.2σ), 3.4σ (5.4σ), 7.1σ (6.6σ) and 11σ (9.7σ) respectively, shown in Figure 2a. The uncertainties of the polarization fractions are dominated by statistical and theory systematic uncertainties. Measurements of the individual polarization fractions of $W^{\pm}$ and Z in $W^{\pm}Z$ final states are described by theory predictions within 1σ. The differential cross-section measurement as a function of $|\cos\theta_V|$, where θ_V denotes the angle of the $W^{\pm}Z$ decay with respect to the $q\bar{q}$ collision axis, is given in Figure 2b. The integrated fiducial cross-section is measured to be $\sigma^{\text{fid}}_{WZ\to\ell'\nu\ell\ell} = 64.6 \pm 0.5\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 1.1\,(\text{lumi})$ fb, with a precision of 3.4% and in agreement with the SM prediction at NNLO in QCD, $\sigma^{\text{fid, SM}}_{WZ\to\ell'\nu\ell\ell} = 64.6^{+1.5}_{-1.3}$ fb.

5. Conclusions

Fiducial differential cross-section measurements of W^+W^-, $Z\gamma$ and $W^{\pm}Z$ production in pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV using data recorded with the ATLAS detector between 2015 and 2018 (LHC's Run 2) are presented with unprecedented precision. The later measurement reports the first observation of doubly-longitudinal polarized $W^{\pm}Z$, along with experimental determinations of joint and individual polarization fractions of the gauge massive vector bosons. State-of-the-art theoretical predictions are in excellent agreement with the experimental results.

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