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W and Z inclusive and differential cross sections at CMS

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We summarize the results of recent studies of the production of W and Z bosons in proton-proton collisions using data collected by the CMS experiment at the CERN Large Hadron Collider during Run I and Run II. The total and differential cross sections measured as a function of various kinematic variables are discussed along with specific studies on the W boson charge asymmetry and the angular coefficients of Z bosons decaying to $\mu^+\mu^-$.

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1. Introduction

Electroweak gauge boson production in proton-proton collisions is an important probe of standard model (SM) gauge boson interactions. The final states of W and Z decays have unique experimental signatures and the production cross sections for these processes are theoretically well understood and sensitive to deviations from the SM. Drell–Yan events are characterized by the presence of two isolated leptons with opposite charge and same flavour, while in W events a lepton with large transverse momentum and missing transverse energy is present. The high production rate at the CERN Large Hadron Collider (LHC), the clean signature, and the good performance and understanding of the CMS detector allow to perform precision tests of perturbative quantum chromodynamics (pQCD) and further constrain the parton distribution functions (PDFs).

2. Inclusive W and Z cross sections

A first measurement of the inclusive W and Z boson production at a center-of-mass energy of 13 TeV was performed by CMS using data collected in 2015 corresponding to an integrated luminosity of 43 ± 2 pb^{-1} [1]. Both electron and muon final states are studied and the total inclusive and fiducial W and Z boson production cross sections were measurement. The measured total inclusive cross sections times branching fractions are $\sigma(\mathrm{pp} \to \mathrm{W}^{+}\mathrm{X}) \times \mathrm{Br}(\mathrm{W}^{+} \to \ell^{+}\nu) = 11370 \pm 50(\mathrm{stat}) \pm 230(\mathrm{syst}) \pm 550(\mathrm{lumi})$ pb, $\sigma(\mathrm{pp} \to \mathrm{W}^{-}\mathrm{X}) \times \mathrm{Br}(\mathrm{W}^{-} \to \ell^{-}\bar{\nu}) = 8580 \pm 50(\mathrm{stat}) \pm 160(\mathrm{syst}) \pm 410(\mathrm{lumi})$ pb, and $\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathrm{Br}(\mathrm{Z} \to \ell^{+}\ell^{-}) = 1910 \pm 10(\mathrm{stat}) \pm 40(\mathrm{syst}) \pm 90(\mathrm{lumi})$ pb for the dilepton mass in the range of 60 to 120 GeV. Fig. 1 (left) shows the measured $\mathrm{W}^{\pm}$ and Z production cross sections and the ratios of the measured results and the theoretical predictions. The measured values agree with next-to-next-to-leading-order (NNLO) QCD cross section calculations. The total uncertainty is dominated by the uncertainty in the luminosity measurement (indicated by the shaded box). An updated measurement of the Z production cross section in the muon final state was performed using the entire 2015 run corresponding to an integrated luminosity of 2.3 fb^{-1} [2]. The measured total inclusive cross section $\sigma(\mathrm{pp} \to \mathrm{ZX}) \times \mathrm{Br}(\mathrm{Z} \to \ell^{+}\ell^{-}) = 1870 \pm 2(\mathrm{stat}) \pm 35(\mathrm{syst}) \pm 51(\mathrm{lumi})$ pb is in very good agreement with NNLO QCD calculations and has substantially improved systematic uncertainties. Fig. 1 (right) shows the measured total W^{+}, W^{-}, W, and Z production cross sections versus center-of-mass energy for CMS and experiments at lower-energy colliders. The NNLO predictions agree with the measurements across the energy ranges probed so far.

3. Differential W and Z cross sections

The transverse momentum distribution of Z bosons is a probe of the strong interaction. The low p_{T} range is governed by initial-state parton radiation (ISR) and the intrinsic transverse momentum of the initial-state parton inside the proton and modeled using soft-gluon resummation or parton shower models. Quark-gluon scattering dominates at high p_{T} and is described by perturbative QCD. The differential $\mathrm{Z} \to \mu^{+}\mu^{-}$ cross section was measured as a function of the transverse momentum, the angular variable ϕ^{*}_{η} and the rapidity of the muon pairs at $\sqrt{s} = 13$ TeV [2] and $\sqrt{s} = 8$ TeV [3]. The Z boson p_{T} is reconstructed from the muon kinematics and is affected by

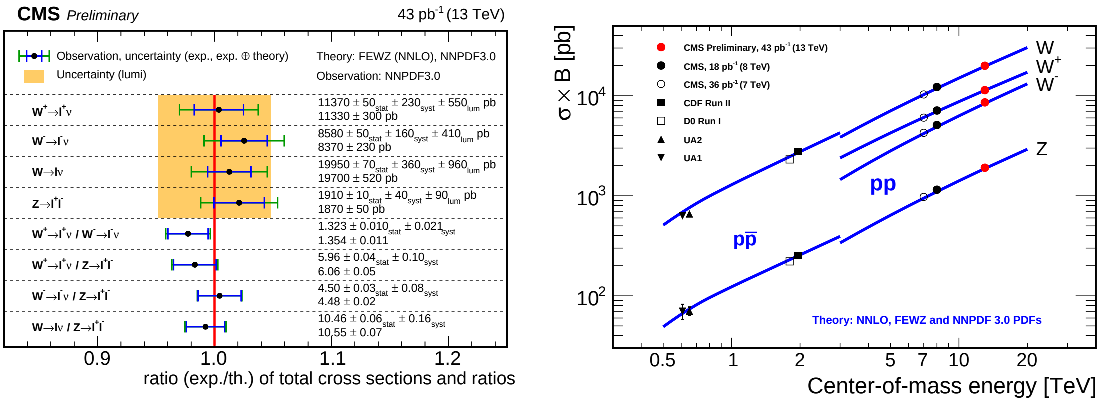

Figure 1: Left: Summary of total inclusive W and Z production cross sections times branching fractions, W to Z and W^+ to W^- ratios, and their theoretical predictions for the electron and muon channel. Right: Measurements of the total W^+, W^-, W, and Z production cross sections times branching fractions versus center-of-mass energy.

muon momentum uncertainties. The observable $\phi^\star_\eta$ probes the p_T of the Z boson but depends uniquely on the direction of the muons, resulting in a smaller experimental uncertainty allowing for very precise comparison with resummation techniques or with different expansion in the perturbation theory. Fig. 2 shows the measured $\phi^\star_\eta$ distribution of the Z boson. The data are corrected for detector effects and compared to MADGRAPH5 AMC@NLO, POWHEG, and FEWZ. Generally, good agreement between the data and the generated distribution is found. However, no generator is able to describe the data in all of the studied phase-space.

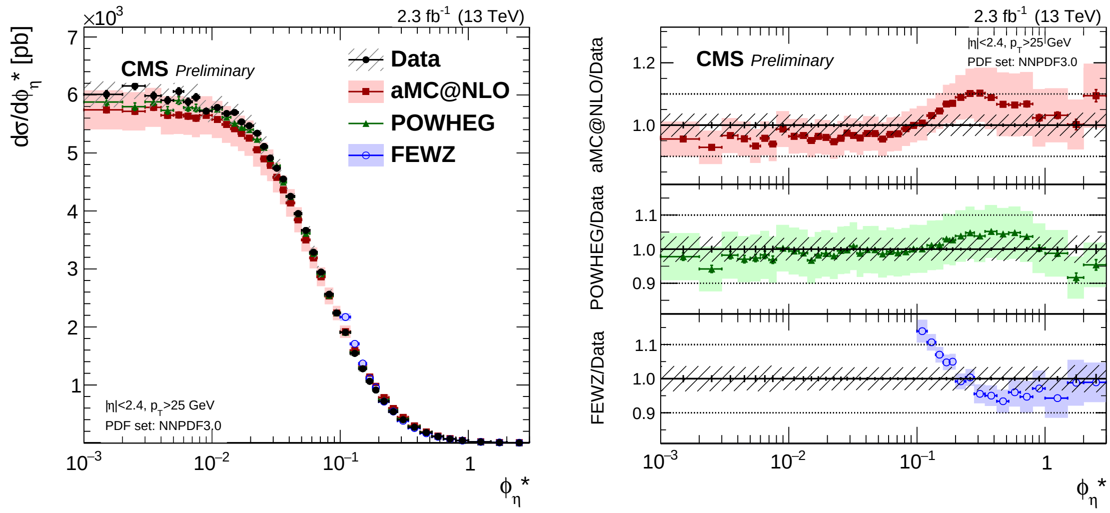

Figure 2: $\phi^\star_\eta$ distribution of the $Z \to \mu^+\mu^-$ boson. The data points (black) are surrounded by the total uncertainty (shaded band) and its statistical component (solid line). FEWZ prediction is shown for $\phi^\star_\eta > 0.1$. The solid band around the MC predictions (of the same color of the marker) represents the total uncertainty, while the solid line, the statistical component.

The differential Drell–Yan cross section $d\sigma/dm$ was measured in the dimuon channel at $\sqrt{s} =$ 13 TeV using the full 2015 dataset corresponding to an integrated luminosity of 2.8 fb^{-1} [4]. The measurement is performed in 43 dimuon invariant mass bins covering a mass range from 15 to 3000 GeV. Events with two isolated muons of opposite charge and $p_{\mathrm{T}} > 22$ (10) GeV are selected. The measurement is corrected for detector resolution effects resulting in event migration between mass bins and reconstruction and trigger efficiencies. In addition the effects of final state radiation (FSR) are taken into account and the the measured cross section is corrected to the full phase space. Fig. 3 shows the measured differential cross section in full phase space with FSR correction (left) and the fiducial cross section without FSR (right). The results are in good agreement with NNLO predictions calculated with FEWZ and NLO predictions calculated with MADGRAPH5 AMC@NLO.

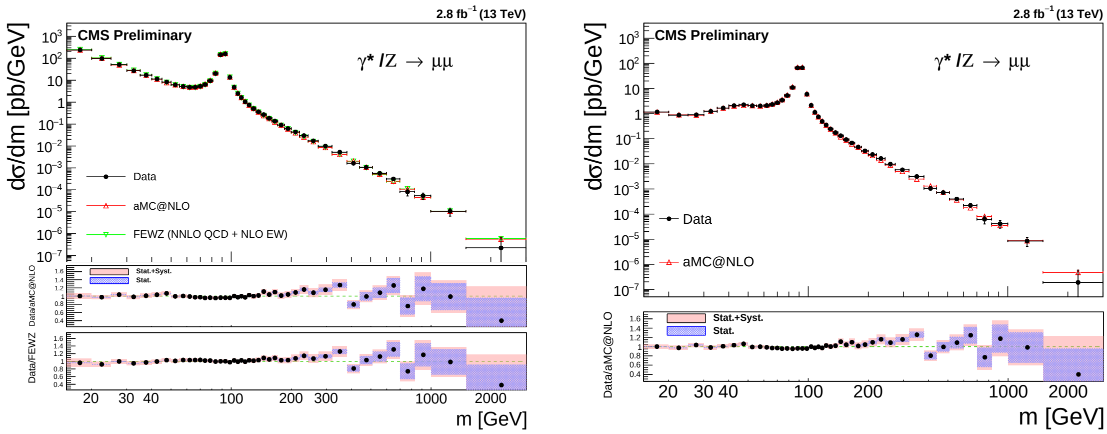

Figure 3: Comparison between the experimental results for full phase space with FSR correction (left) and the fiducial cross section without FSR correction (right) and the NLO theoretical prediction using MADGRAPH5 AMC@NLO. On the bottom plot, the band with red colour denotes total uncertainty which is the combination of statistical, systematical, and luminosity uncertainty. The band with purple colour denotes the statistical uncertainty only.

4. W charge asymmetry

In proton-proton collisions the dominant W boson production occurs through the annihilation of a valence quark from one of the protons with a sea antiquark from the other: $\mathrm{u\bar{d}} \to \mathrm{W}^+$ and $\mathrm{d\bar{u}} \to \mathrm{W}^-$. Because of the presence of two valence u quarks in the proton, W^+ bosons are produced more often than W^- bosons. A precise measurement of the charge asymmetry as a function of the muon η,

$$A(\eta) = \frac{d\sigma/d\eta(\mathrm{W}^+ \to \ell^+\nu) - d\sigma/d\eta(\mathrm{W}^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(\mathrm{W}^+ \to \ell^+\nu) + d\sigma/d\eta(\mathrm{W}^- \to \ell^-\bar{\nu})}$$

provides significant constraints on the ratio of u and d quark distributions in the proton for values of the Bjorken scaling variable x between $10^{-3} < x < 10^{-1}$. The differential cross section and charge asymmetry of the $\mathrm{W} \to \mu\nu$ production in pp collisions was measured by the CMS collaboration at $\sqrt{s} = 8$ TeV using a data sample corresponding to an integrated luminosity of 18.8 fb^{-1} [5].

The measurements were performed in 11 bins of absolute muon pseudorapidity $|\eta|$ for muons with $p_{\mathrm{T}} > 25$ GeV. Fig. 4 (left) shows the measured charge asymmetry. The error bars of the measurements represent both statistical and systematic uncertainties, including the uncertainty in the integrated luminosity. The measurements are compared with theoretical predictions based on several PDF sets. The results have been incorporated into a QCD analysis at next-to-next-to leading-order together with the inclusive deep inelastic scattering data from HERA. A significant improvement in the accuracy of the valence quark distributions is observed in the range $10^{-3} < x < 10^{-1}$, demonstrating the power of these muon charge asymmetry measurements to improve the main constraints on the valence distributions imposed by the HERA data, in the kinematics range probed. By adding these muon charge asymmetry measurements, the constraints can be significantly improved, as illustrated in Fig. 4 (right) where the x_{d} valence distribution is shown at the scale of m_{W}^2, relevant for the W boson production.

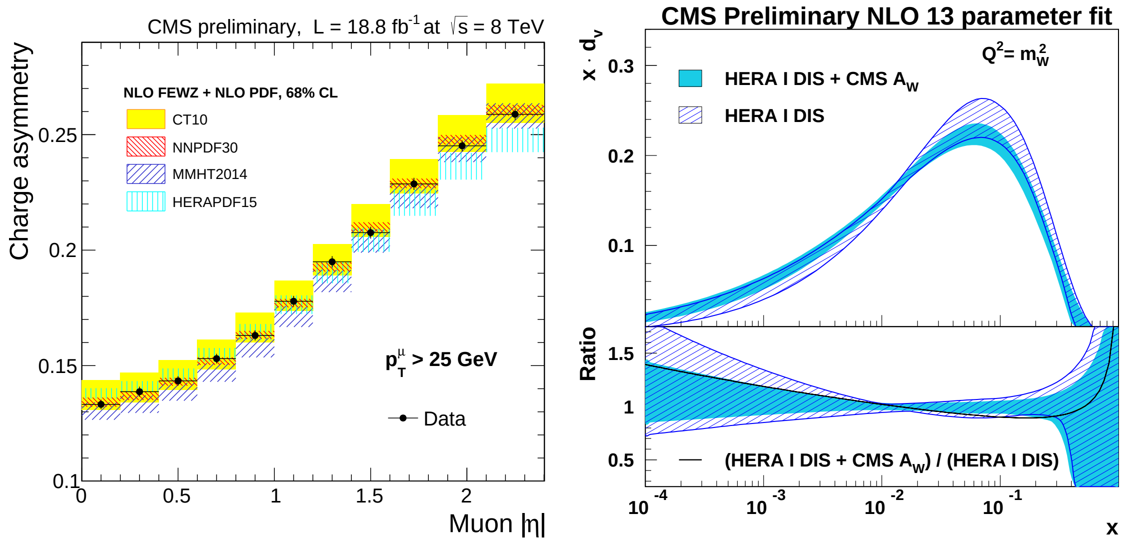

Figure 4: Left: Comparison of the measured muon charge asymmetries to NLO predictions calculated using the FEWZ 3.1 MC tool interfaced with four different PDF sets. The vertical error bars on data points include both statistical and systematic uncertainties. The PDF uncertainty for each PDF set is shown by the shaded (or hatched) band and corresponds to 68% CL. The NNPDF3.0 and MMHT2014 PDF fits include previous lepton charge asymmetries measured by CMS at $\sqrt{s} = 7$ TeV. Right: Distributions of d valence quarks as functions of x at the scale $Q^2 = m_{\mathrm{W}}^2$. The results of the fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

5. Angular coefficients of Z bosons

A set of measurements of the five most significant angular coefficients, A_0 through A_4, for Z bosons produced in pp collisions at $\sqrt{s} = 8$ TeV and decaying to $\mathrm{Z} \to \mu^+\mu^-$ was performed by the CMS collaboration [6]. The integrated luminosity of the dataset used for this measurement corresponds to 19.7 fb^{-1}. The angular coefficients are measured in 8 q_{T} bins and 2 rapidity bins

($|\eta| < 1$, $1 < |\eta| < 2.1$). These measurements provide comprehensive information about Z boson production mechanisms, and are compared to QCD predictions at leading order, next-to-leading order, and next-to-next-to-leading order in perturbation theory. Fig. 5 shows the angular coefficients A_4 and $A_0 - A_2$ measured in the Collins-Soper frame for $|y| < 1$. MadGraph and FEWZ describe most measurements well (except A_4). Some theoretical predictions deviate from the measurements in q_T and no model perfectly captures the measured distributions. The results play an important role in future high-precision measurements, such as the measurement of the mass of the W boson and of the electroweak mixing angle. Further refinements of the theory are needed to achieve a better agreement with the experimental results.

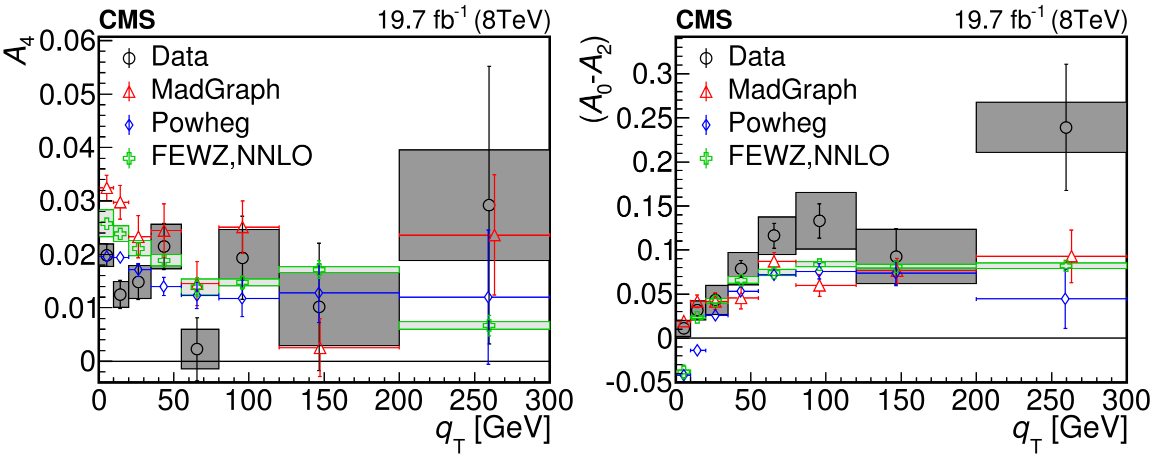

Figure 5: Comparison of the angular coefficients A_4 and $A_0 - A_2$ measured in the Collins-Soper frame for $|y| < 1$. The circles show the measured results. The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement. The triangles show the predictions from MADGRAPH, the diamonds from POWHEG, and the crosses from FEWZ at NNLO. The boxes at the FEWZ values indicate the PDF uncertainties.

References

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