# Electroweak Precision Measurements with Z Bosons at the LHC

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Measurements of the forward-backward asymmetry in the neutral current annihilation process $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$, where $\ell$ denotes a muon or electron, at the LHC are reported. The forward-backward asymmetry is measured as a function of the dilepton invariant mass yielding the effective weak mixing angle. The effective weak mixing angle values of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.2308 \pm 0.0012$ and $\sin^2\theta_{\rm eff}^{\rm lept} = 0.2314 \pm 0.0011$ are obtained by the ATLAS and LHCb collaborations, respectively. The results are in agreement with the current world average.

## 1 Introduction

The electroweak fit of the Standard Model (SM) of particles is overconstrained with the inclusion of the Higgs boson mass in the fit [1]. The leptonic effective weak mixing angle and the $W$ boson mass are predicted to be $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23149 \pm 0.00007$ and $M_W = 80.358 \pm 0.008$ GeV, respectively, with a precision exceeding that of the corresponding direct measurements. Inconsistencies between direct measurements of key electroweak observables and predictions could indicate physics beyond the SM.

The most precise measurements of $\sin^2\theta_{\rm eff}^{\rm lept}$ have been performed at the LEP and SLD electron-positron colliders[2]. The combination of all these measurements gives a value of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23153 \pm 0.00016$. However, there is a tension between the two most precise single measurements differing by approximately three standard deviations. The SLD polarized left-right asymmetry measurement gives a value of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23098 \pm 0.00026$, while the forward-backward asymmetry in b-quark final states at the LEP gives a value of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23221 \pm 0.00029$.

Measurements at the Tevatron and LHC reaching this level of precision will help to resolve the discrepancy. The CDF measurement of forward-backward asymmetry in the polar angle distribution of the Drell-Yan ($Z/\gamma*$) lepton pairs in electron and muon final states gives a value of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23221 \pm 0.00046$ [3]. The D0 measurement in the electron final state gives a value of $\sin^2\theta_{\rm eff}^{\rm lept} = 0.23146 \pm 0.00047$ [4]. The systematic uncertainties are small compared to the statistical uncertainties in the CDF and D0 measurements.

## 2 Forward-backward asymmetry at the LHC

The difference of vector and axial-vector couplings of the $Z$ boson to fermions results in a forward-backward asymmetry ($A_{\mathrm{FB}}$) in the angular distribution of positively and negatively charged leptons produced in the Dell-Yan process. The differential cross section at leading order is given by

$$\frac{d\sigma}{d(\cos\theta)} = A(1+\cos^2\theta) + B\cos\theta, \tag{1}$$

where $\theta$ is the angle of the negatively charged lepton relative to the quark momentum in the rest frame of the dilepton system, and $A$ and $B$ parameters depend on the dilepton invariant mass, the color charge of incoming quarks, and the weak isospin. In addition, the parameter $B$ depends on the weak mixing angle $\sin^2\theta_W$. The asymmetry $A_{FB}$ is defined as

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}, \tag{2}$$

where $\sigma_{\mathrm{F}}$ denotes the total cross section of the events with $\cos\theta > 0$ (forward) and $\sigma_{\mathrm{B}}$ denotes the total cross section of the events with $\cos\theta < 0$ (backward).

The lepton pairs in proton-proton (pp) collisions are produced mainly from the annihilation of valence quarks with sea antiquarks. The transverse momentum ($p_T$) of the incoming (anti)quark introduces an uncertainty in the $A_{\mathrm{FB}}$ measurement as the four-momentum of the (anti)quark is not determined in the dilepton rest frame. Therefore, the $A_{\mathrm{FB}}$ measurements are performed in the Collins-Soper (CS) frame [5] to minimize the impact of this effect. The $z$-axis is aligned with the difference of the incoming proton momentum vectors in the dilepton rest frame in the CS frame. However, the sign of $\cos\theta$ is not known as both beams consist of protons at the LHC. The positive axis is defined to be along the longitudinal boost of the dilepton system in the laboratory frame taking into account that a valence quark, on average, carries more momentum than a sea antiquark. The definition, however, does not always yield an incoming quark having a positive $z$-axis component of the momentum vector resulting in a dilution of the $A_{\mathrm{FB}}$. The dilution effect is reduced for larger rapidities where the $Z$ boson has a large longitudinal momentum and tends to be boosted along the direction of the quark.

## 3 Measurements of the $A_{\mathrm{FB}}$

Measurements of the $A_{\mathrm{FB}}$ have been performed by the ATLAS, CMS, and LHCb collaborations. Dimuon and dielectron final states have been used by the CMS collaboration in pp collisions at $\sqrt{s} = 8$ TeV with a data sample corresponding to an integrated luminosity of 19.7 $\mathrm{fb}^{-1}$ collected with the CMS detector [6]. The $A_{\mathrm{FB}}$ measurement is performed as a function of the dilepton invariant mass between 40 GeV and 2 TeV in four and five dilepton absolute rapidity $|y|$ bins up to $|y| = 2.4$ and $|y| = 5.0$ in the muon and electron final states, respectively. Electrons in the range of $3 < |\eta| < 5$, where $\eta$ is the pseudorapidity, are measured by the hadron forward calorimeters [7].

Dimuon final state has been used by the LHCb collaboration in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV with data samples corresponding to integrated luminosities of 1 $\mathrm{fb}^{-1}$ and 2 $\mathrm{fb}^{-1}$, respectively [11]. The $A_{\mathrm{FB}}$ measurement is performed as a function of the dimuon invariant mass between 60 GeV and 160 GeV using muons with $p_T > 20$ GeV and $2.0 < \eta < 4.6$. The kinematic phase space probed by the LHCb detector [12] reduces the dilution effect discussed in Section 2.

The $A_{\mathrm{FB}}$ in dimuon and dielectron final states has also been measured by the ATLAS collaboration in pp collisions at $\sqrt{s} = 7$ TeV with a data sample corresponding to an integrated luminosity of 4.8 $\mathrm{fb}^{-1}$ collected with the ATLAS detector [13,14]. The measurement is performed as a function of the dilepton invariant mass between 66 GeV and 1 TeV using central leptons, and up to 250 GeV in the electron final states where one electron is measured in the range of $2.5 < |\eta| < 4.9$.

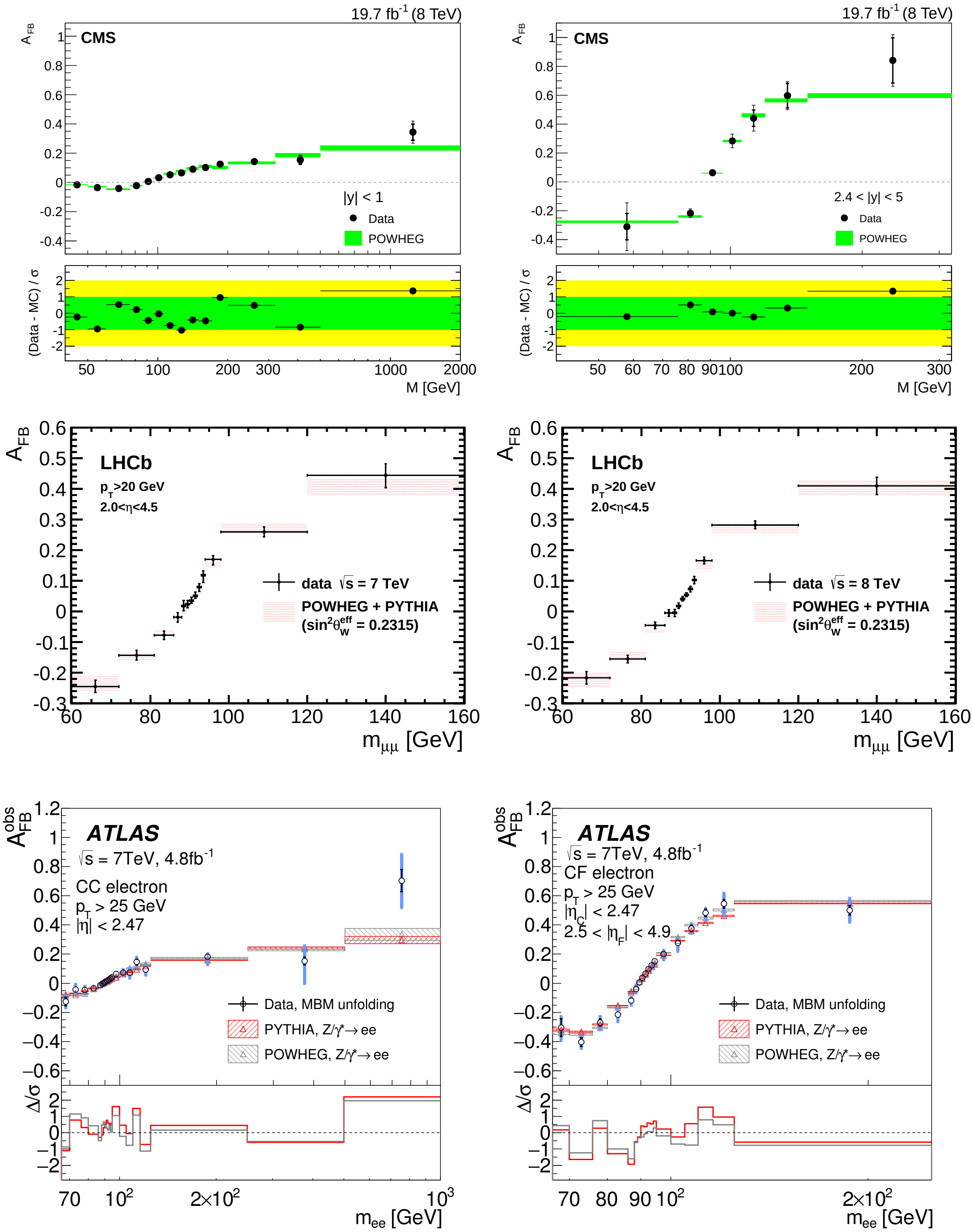


Figure 1 – Measured $A_{\mathrm{FB}}$ values in selected rapidity regions with the CMS (top panel), LHCb (middle panel), and ATLAS (bottom panel) detectors. Inner (outer) vertical bars show the statistical (statistical plus systematics) uncertainties. The measurements are compared with POWHEG [8,9] and PYTHIA [10] predictions using the world average value of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$. The shaded bands represent the uncertainties in the prediction described in the original articles [6,11,14].

Figure 1 shows the results for selected rapidity bins. The ATLAS and CMS $A_{\mathrm{FB}}$ values are corrected for the detector resolution, acceptance, and final state radiation effects. The measurements are consistent with the corresponding Standard Model predictions. The $A_{\mathrm{FB}}$ is large and negative (positive) for dilepton invariant masses below 80 GeV (above 110 GeV) due to interference with a virtual photon while the $A_{\mathrm{FB}}$ is close to zero near the $Z$ boson pole mass because of the small value of lepton vector coupling to the $Z$ boson. The $A_{\mathrm{FB}}$ is diluted less in the forward rapidity region as discussed above.

## 4 Measurements of the $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ with the ATLAS and LHCb detectors

The forward-backward asymmetry values are used to extract the value of the $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ with most of the sensitivity coming from the dilepton invariant masses near the $Z$ pole. The measured $A_{\mathrm{FB}}$ also depends on the quark effective weak mixing angle. However, the effect on the $A_{\mathrm{FB}}$ is an order of magnitude smaller than the effect of the $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$.

Templates of $A_{\mathrm{FB}}$ are calculated using different values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ and compared to the measurement to determine the value of the parameter that best describes the data. The ATLAS collaboration reports a value of

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}), \tag{3}$$

where PDF denotes the uncertainty in the knowledge of the proton parton distribution functions (PDFs). The LHCb collaboration reports a value of

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23142 \pm 0.00073(\mathrm{stat.}) \pm 0.00052(\mathrm{syst.}) \pm 0.00056(\mathrm{theo.}), \tag{4}$$

where the theoretical uncertainty includes the uncertainty in the PDF, choice of the renormalization and factorization scales, the uncertainty in strong coupling constant $\alpha_s$, and the implementation of the final state radiation. The dominant experimental systematic uncertainty is due to electron and muon energy scale and resolution. The measured values by the ATLAS and LHCb collaborations agree with the other measurements as shown in Figure 2.

The statistical uncertainties of the current $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ measurements at the LHC are large and future measurements with more data will result in better precision. Improved measurement techniques should further improve the precision.

## 5 Gauge Boson production and PDF

The uncertainty resulting from the knowledge of the PDF is the dominant theoretical uncertainty. For example, the dilution effects depend on the knowledge of sea-to-valence quark ratio within the accessible Bjorken-x range. The LHCb experiment has smaller theoretical uncertainties as the dilution is small in the forward region of the kinematic phase space. High precision measurements of the gauge boson production cross sections at the LHC provide further constraints on the PDF. ATLAS, CMS, and LHCb collaborations have measured $W$ and $Z$ boson inclusive total, fiducial, and differential production cross sections and their ratios in pp collisions at $\sqrt{s} = 7$ TeV, 8 TeV, and 13 TeV. Precise measurements are performed in muon and electron final states.

The ATLAS collaboration has performed high-precision measurements of the inclusive $W^{\pm}$ and $Z/\gamma^*$ production cross sections[16] using muon and electron final states in pp collisions at $\sqrt{s} =$ 7 TeV with a data sample corresponding to an integrated luminosity of 4.6 fb$^{-1}$. The differential $W^{\pm}$ production cross sections and the lepton charge asymmetry $A_\ell = (d\sigma^- - d\sigma^-)/(d\sigma^+ - d\sigma^-)$ are measured as a function of the lepton pseudorapidity of up to $\eta = 2.5$. The differential $Z/\gamma^*$ production cross sections are measured as a function of the dilepton rapidity of up to $|y| < 3.6$ in three bins of the dilepton invariant mass.

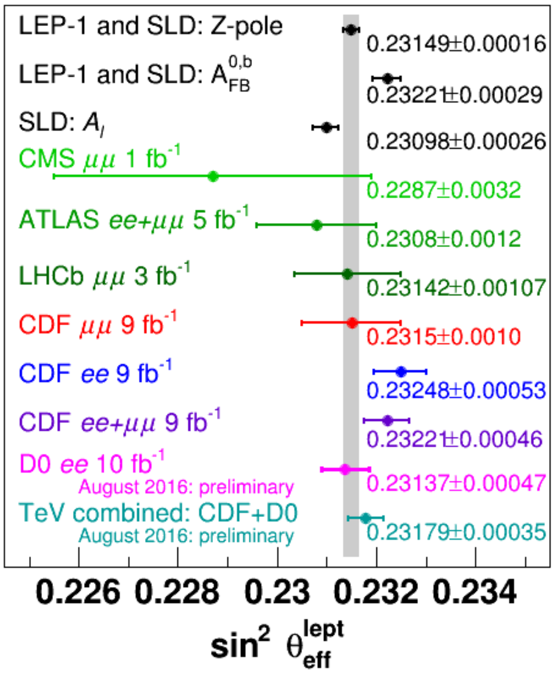


Figure 2 – Measurements of the $\sin^2\theta^{\rm lept}_{\rm eff}$ at the LHC and at other colliders [15]. The LEP and SLD combined measurement is shown by the vertical gray band.

The LHCb collaboration has measured the $Z/\gamma^*$ production cross section [17] using muon and electron final states in pp collisions at $\sqrt{s}$ = 13 TeV with a data sample corresponding to an integrated luminosity of 0.294 fb$^{-1}$. The production cross section is measured for lepton pseudorapidities in the range of $2.0 < \eta < 4.5$. The LHCb measurements probe low and high values of Bjorken-x since a longitudinal boost is needed to produce the gauge bosons in the forward region. The lepton charge asymmetry has also been measured [18,19] using muon and electron final states in pp collisions at $\sqrt{s}$ = 8 TeV with a data sample corresponding to an integrated luminosity of 2.0 fb$^{-1}$.

The LHCb collaboration has measured the $Z/\gamma^*$ production cross section using muon final states in pp collisions at $\sqrt{s}$ = 13 TeV with a data sample corresponding to an integrated luminosity of 2.3 fb$^{-1}$ [20]. The differential cross sections are measured as a function of dilepton rapidity of up to $|y| < 2.5$. The lepton charge asymmetry has also been measured using muon final states in pp collisions at $\sqrt{s}$ = 8 TeV with a data sample corresponding to an integrated luminosity of 18.8 fb$^{-1}$ [21].

Figure 3 shows a selection of measurements of the lepton charge asymmetry (left column) and the $Z/\gamma^*$ production differential cross sections (right column) with the CMS (top panel), LHCb (middle panel), and ATLAS (bottom panel) detectors. The lepton charge asymmetry measurement constrains the valence and sea quark distributions. The measurements show good agreement with predictions at accuracy of NNLO using different PDF sets. Future measurements at the LHC with increased precision will provide strong constraints on the PDF.

The ATLAS and CMS collaborations have interpreted these measurements using a QCD analysis together with the inclusive deep inelastic scattering data from HERA [22]. The CMS collaboration reports a significant improvement in the accuracy of the valence quark distributions. The ATLAS collaboration reports an accurate determination of strange-to-light sea-quark densities with larger than expected strangeness fraction of the light sea.

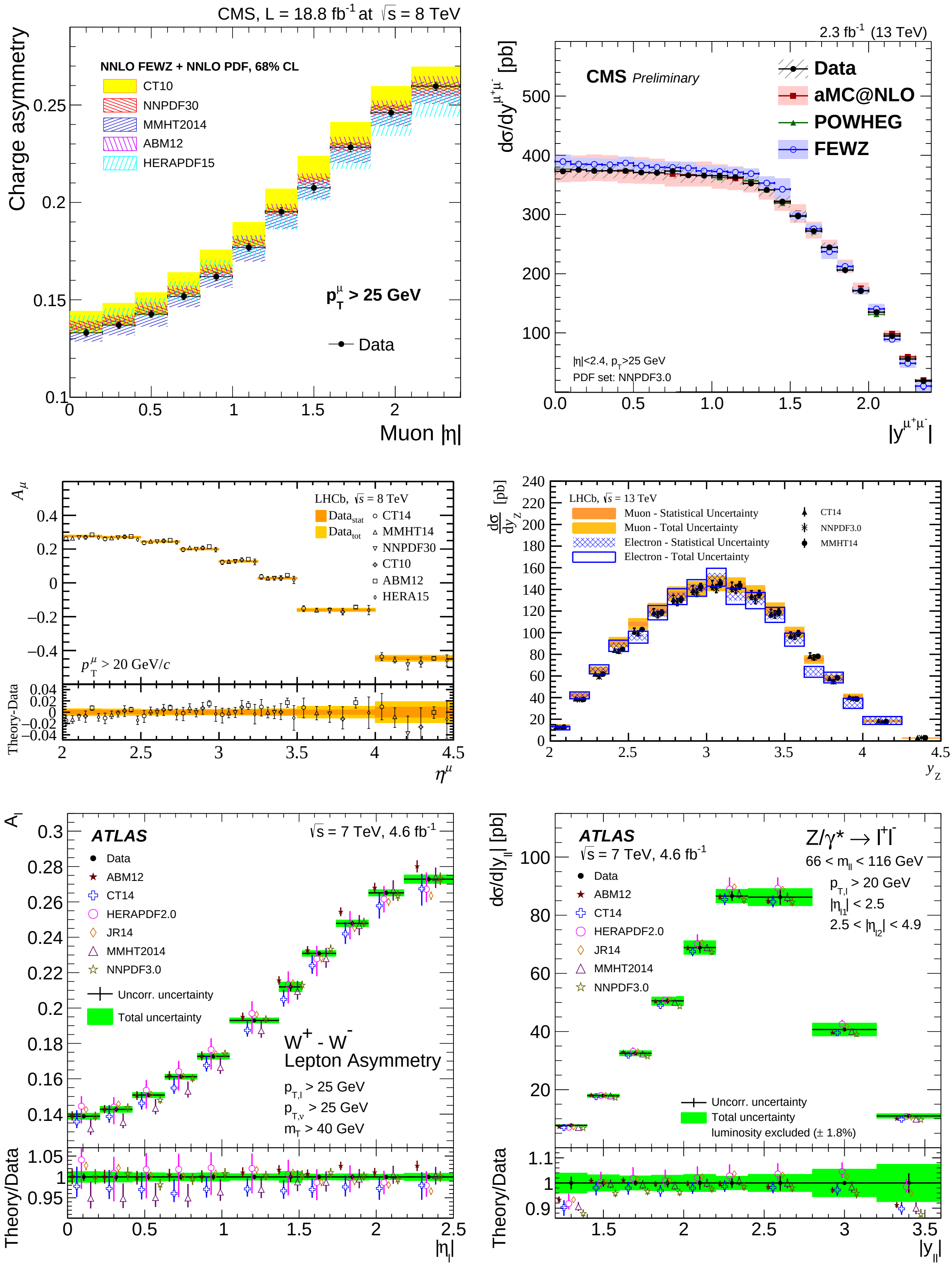


Figure 3 – Measurements of the lepton charge asymmetry as a function of the lepton pseudorapidity (left column) and measurements of the $Z\gamma^*$ production differential cross sections as a function of the boson rapidity with the CMS (top panel), LHCb (middle panel), and ATLAS (bottom panel) detectors. The measurements are compared to NNLO pQCD calculations using different PDF sets.

## 6 Conclusions

Measurements of the $\sin^2\theta_{\rm eff}^{\rm lept}$ by the ATLAS and LHCb collaborations agree with previous measurements at other colliders. The statistical uncertainties are still large and future measurements will provide improved precision. The PDF uncertainties are the dominant theoretical uncertainties. Precision measurements of the gauge boson production cross sections provide important constraints on the PDF. Thus, future measurements of the $\sin^2\theta_{\rm eff}^{\rm lept}$ at the LHC may become important inputs to the electroweak global fits.

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