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Measurement of the muon charge asymmetry in inclusive $pp \rightarrow W + X$ production at $\sqrt{s} = 7$ TeV and an improved determination of light parton distribution functions

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Abstract

Measurements of the muon charge asymmetry in inclusive $pp \rightarrow W + X$ production at $\sqrt{s} = 7$ TeV are presented. The data sample corresponds to an integrated luminosity of 4.7 fb^{-1} recorded with the CMS detector at the LHC. With a sample of more than twenty million $W \rightarrow \mu\nu$ events, the statistical precision is greatly improved in comparison to previous measurements. These new results provide additional constraints on the parton distribution functions of the proton in the range of the Bjorken scaling variable x from 10^{-3} to 10^{-1} . These measurements and the recent CMS measurement of associated $W + \text{charm}$ production are used together with the cross sections for inclusive deep inelastic $e^\pm p$ scattering at HERA in a next-to-leading-order QCD analysis. The determination of the valence quark distributions is improved, and the strange-quark distribution is probed directly through the leading-order process $g + s \rightarrow W + c$ in proton-proton collisions at the LHC.

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1 Introduction

In the standard model (SM), the dominant processes for inclusive W-boson production in pp collisions are annihilation processes: $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$ involving a valence quark from one proton and a sea antiquark from the other. Since there are two valence u quarks and one valence d quark in the proton, W^+ bosons are produced more often than W^- bosons. The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) has investigated this production asymmetry in inclusive W-boson production and measured the inclusive ratio of total cross sections for W^+ and W^- boson production at $\sqrt{s} = 7$ TeV to be 1.421 ± 0.006 (stat.) ± 0.032 (syst.) [1]. This result is in agreement with SM predictions based on various parton distribution functions (PDFs) such as the MSTW2008 and CT10 PDF sets [2, 3]. Measurements of the production asymmetry between W^+ and W^- bosons as a function of boson rapidity can provide additional constraints on the d/u ratio and on the sea antiquark densities in the proton. For pp collisions at $\sqrt{s} = 7$ TeV, these measurements explore the PDFs for the proton for Bjorken x from 10^{-3} to 10^{-1} [4]. However, it is difficult to measure the boson rapidity production asymmetry because of the energy carried away by neutrinos in leptonic W-boson decays. A quantity more directly accessible experimentally is the lepton charge asymmetry, defined as

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \ell^-\bar{\nu})}, \quad (1)$$

where $d\sigma/d\eta$ is the differential cross section for W-boson production and subsequent leptonic decay and $\eta = -\ln[\tan(\theta/2)]$ is the charged lepton pseudorapidity in the laboratory frame, with θ being the polar angle measured with respect to the beam axis.

High precision measurements of the W-boson lepton charge asymmetry can improve the determination of the PDFs. Both the W-boson lepton charge asymmetry and the W-boson production charge asymmetry were studied in $p\bar{p}$ collisions by the CDF and D0 experiments at the Tevatron collider [5–7]. The ATLAS, CMS, and LHCb experiments also reported measurements of the lepton charge asymmetry using data collected at the LHC in 2010 [8–11]. An earlier measurement of the W-boson electron charge asymmetry is based on 2011 CMS data corresponding to an integrated luminosity of 0.84 fb^{-1} [12].

The impact of CMS measurements of the lepton charge asymmetry on the global PDF fits has been studied by several groups [13–17], who concluded that improvements in the PDF uncertainties for several quark flavors could be achieved with more precise data. In this paper, we report a measurement of the muon charge asymmetry using a data sample corresponding to an integrated luminosity of 4.7 fb^{-1} collected with the CMS detector at the LHC in 2011. The number of $W \rightarrow \mu\nu$ events (more than 20 million) in this data sample is two orders of magnitude larger than for our previous measurement [10].

This precise measurement of the muon charge asymmetry and the recent CMS measurement of associated W + charm production [18] are combined with the cross sections for inclusive deep inelastic $e^\pm p$ scattering at HERA [19] in a quantum chromodynamics (QCD) analysis at next-to-leading order (NLO). The impact of these measurements of W-boson production at CMS on the determination of light-quark distributions in the proton is studied and the strange-quark density is determined.

This paper is organized as follows. A brief description of the CMS detector is given in Section 2. The selection of $W \rightarrow \mu\nu$ candidates is described in Section 3. The corrections for residual charge-specific bias in the measurement of the muon transverse momentum (p_T) and

in the muon trigger, reconstruction, and selection efficiencies are discussed in Section 4. The extraction of the $W \rightarrow \mu\nu$ signal is described in detail in Section 5. Systematic uncertainties and the full correlation matrix are given in Section 6. The final measurements are presented in Section 7 and the QCD analysis is discussed in detail in Section 8. The summary and conclusion follow in Section 9.

2 The CMS experiment

The central feature of the CMS apparatus is a superconducting solenoid 6 m in diameter and 13 m long, which provides an axial field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel flux return yoke. The ECAL consists of nearly 76 000 lead tungstate crystals that provide coverage in pseudorapidity $|\eta| < 1.479$ in the barrel region and $1.479 < |\eta| < 3.0$ in the two endcap regions. A preshower detector consisting of two planes of silicon sensors interleaved with a total of three radiation lengths of lead is located in front of the ECAL endcaps. Muons are selected in the pseudorapidity range $|\eta| < 2.4$, with detection planes constructed of drift tubes (DT), cathode strip chambers (CSC), and resistive plate chambers (RPC), and matched to the tracks measured in the silicon tracker resulting in an η -dependent p_T resolution of about 1–5% for muon p_T up to 1 TeV. The inner tracker, consisting of 1440 silicon pixel and 15 148 silicon strip detector modules, measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of $\sim 15 \mu\text{m}$ and a p_T resolution of about 1.5% for 100 GeV particles.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing towards the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise-beam direction. The polar angle, θ , is measured from the positive z axis and the azimuthal angle, ϕ , is measured in the x - y plane.

A detailed description of the CMS experiment can be found in Ref. [20].

3 Event reconstruction

The signature of a $W \rightarrow \mu\nu$ event is a high- p_T muon accompanied by missing transverse momentum $\vec{\cancel{E}}_T$ due to the escaping neutrino. The CMS experiment has utilized a particle-flow algorithm in event reconstruction, and the $\vec{\cancel{E}}_T$ used by this analysis is determined as the negative vector sum of the transverse momenta of all particles reconstructed by this algorithm [21]. The $W \rightarrow \mu\nu$ candidates were collected with a set of isolated single-muon triggers with different p_T thresholds, which is the major difference with respect to the previous CMS measurement where nonisolated single-muon triggers were used [10]. The isolated muon trigger requires that in the neighboring region of the muon trigger candidate both the transverse energy deposits in calorimeters and the scalar sum of the p_T of the reconstructed tracks are small, and it reduces the trigger rate while maintaining a relatively low muon p_T threshold. We use all the data-taking periods during which the isolated muon triggers were not prescaled (i.e. they were exposed to the full integrated luminosity).

Other physics processes can produce high- p_T muons and mimic $W \rightarrow \mu\nu$ signal candidates. We consider the SM background contributions from multijet production (QCD background), Drell–Yan ($Z/\gamma^* \rightarrow \ell^+\ell^-$) production, $W \rightarrow \tau\nu$ production (electroweak or EW background),

and top-quark pair ($t\bar{t}$) production. In addition, cosmic-ray muons can penetrate through the center of the CMS detector and also mimic $W \rightarrow \mu\nu$ candidates.

Monte Carlo (MC) simulations are used to help evaluate the background contributions in the data sample and to study systematic uncertainties. Primarily, we use NLO MC simulations based on the POWHEG event generator [22] where the NLO CT10 PDF model [3] is used. The τ lepton decay in the $W \rightarrow \tau\nu$ process is simulated by the TAUOLA MC package [23]. We simulate the QCD background with the PYTHIA event generator [24] where the CTEQ6L PDF model [25] is used. The CMS detector simulation is interfaced with GEANT4 [26]. All generated events are first passed through the detector simulation and then reconstructed in the same way as the collision data. Pileup (PU) is the presence of multiple interactions recorded in the same event. For the data used in this analysis, there are an average of about 7 reconstructed primary interaction vertices for each beam crossing. The MC simulation is generated with a different PU distribution than we observe in the data. Therefore, the MC simulation is weighted so that the number of interactions per crossing matches that in data.

The selection criteria for muon reconstruction and identification are described in detail in a previous report [27]. Therefore, only a brief summary is given here. A muon candidate is reconstructed using two different algorithms: one starts with a track measured by the silicon tracker and then requires a minimum number of matching hits in the muon detectors, and the other starts by finding a track in the muon system and then matching it to a track measured by the silicon tracker. Muons used in this measurement are required to be reconstructed by both algorithms. A global track fit, including both the silicon tracker hits and muon chamber hits, is performed to improve the quality of the reconstructed muon candidate. The track p_T measured by the silicon tracker is used as the muon p_T and the muon charge is identified from the signed curvature. Cosmic-ray contamination is reduced by requiring that the distance of closest approach to the leading primary vertex is small: $|d_{xy}| < 0.2$ cm. The remaining cosmic-ray background yield is estimated to be about 10^{-5} of the expected $W \rightarrow \mu\nu$ signal, and is therefore neglected [10]. The track-based muon isolation, $\text{Iso}_{\text{track}}$, is defined to be the scalar sum of the p_T of additional tracks in a cone with a radius of 0.3 around the muon candidate ($R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$, with $\Delta\phi$ and $\Delta\eta$ being the differences between the muon candidate and the track in η - ϕ plane). Muons are required to have $\text{Iso}_{\text{track}}/p_T < 0.1$. Only muons within $|\eta| < 2.4$ are included in the data sample.

In each event, muons passing the above selection criteria are ordered according to p_T , and the leading muon is selected as the $W \rightarrow \mu\nu$ candidate. The leading muon is required to be the particle that triggered the event. In addition, the muon is required to have $p_T > 25$ GeV, which is safely above the trigger turn-on thresholds. Events that have a second muon with $p_T > 15$ GeV are rejected to reduce the background from Drell–Yan dimuon events (“Drell–Yan veto”). The rejected events, predominantly $Z/\gamma^* \rightarrow \mu^+\mu^-$ events, are used as a Drell–Yan control sample to study the modeling of the $\vec{\cancel{E}}_T$ and also to provide constraints on the modeling of the p_T spectrum of W and Z bosons. In addition, this sample is used to estimate the level of background from Drell–Yan events where the second muon is not identified. The muon is corrected for a bias in the measurement of the momentum (discussed below) prior to the application of the p_T selection.

The $W \rightarrow \mu\nu$ candidates that pass the above selection criteria are divided into 11 bins in absolute value of muon pseudorapidity $|\eta|$. The bin width is 0.2, except that the last three $|\eta|$ bins are [1.6–1.85], [1.85–2.1], and [2.1–2.4], respectively. The muon charge asymmetry is measured in each of the $|\eta|$ bins, along with the determination of the correlation matrix of the systematic uncertainties between different $|\eta|$ bins.

4 Muon momentum correction and efficiency studies

The measured momentum of the muon depends critically on the correct alignment of the tracker system and the details of the magnetic field. Even after the alignment of the tracker detector a residual misalignment remains, which is not perfectly reproduced in the MC simulation. This misalignment leads to a charge dependent bias in the reconstruction of muon momenta, which is removed by using a muon momentum correction. The detailed description of the method for the extraction of the correction factors using $Z/\gamma^* \rightarrow \mu^+\mu^-$ events is given in Ref. [28]. Here we provide only a short summary of the method. First, corrections to muon momentum in bins of η and ϕ are extracted separately for positively and negatively charged muons using the average of the $1/p_T$ spectra of muons in $Z/\gamma^* \rightarrow \mu^+\mu^-$ events. The mean values of the $1/p_T$ spectra at the MC generator level, varied by the reconstruction resolution, are used as a “reference”. The mean values of the reconstructed $1/p_T$ spectra in data or simulation are tuned to match the reference. Second, the correction factors derived in the previous step are tuned further by comparing the dimuon invariant mass in each bin of muon charge Q and η to the ones at the MC generator level varied by the reconstruction resolution. By comparing the correction factors for positively and negatively charged muons in each bin, we can determine relative corrections from misalignment and from uncertainties in the magnetic field in the tracker system. We find that the bias is predominantly from misalignment. The same procedure is performed for both data and reconstructed MC events, and correction factors are determined separately.

The average of the dimuon invariant mass (mass profile) as a function of muon Q and η before and after the $1/p_T$ tuning is shown in Fig. 1. The dimuon mass profiles after the correction are compared to the reference mass profile for data and MC simulation. They agree well with the reference, so the muon momentum bias is largely removed. The reference mass profile is expected to be a function of η because of the p_T requirements for the two daughter muons in $Z/\gamma^* \rightarrow \mu^+\mu^-$ decays. The correction factors are extracted using the same η binning defined above in order to avoid correlations between different η bins.

The overall efficiency in the selection of muon candidates includes contributions from reconstruction, identification (including isolation), and trigger efficiencies. The muon reconstruction efficiency includes contributions from the reconstruction efficiency in the tracker system (“tracking”) and in the muon system. The muon “offline” efficiency is the product of reconstruction and identification efficiencies. The contribution of each component to the overall efficiency (tracking, muon standalone reconstruction, identification, and trigger) is measured directly from the $Z/\gamma^* \rightarrow \mu^+\mu^-$ events using the tag-and-probe method [1, 27]. In this method one of the daughter muons is used to tag the $Z/\gamma^* \rightarrow \mu^+\mu^-$ event and the other muon candidate is used as a probe to study the muon efficiencies as a function of Q , η , and p_T . For every event a positively charged muon can be selected as the tag and a negatively charged probe candidate is used to study the efficiencies for negatively charged muons. The same procedure is repeated by selecting a negatively charged muon as the tag to study efficiencies for positively charged muons. Each individual efficiency is determined in 22 bins of muon η , as defined above, and 7 bins of p_T (15–20, 20–25, 25–30, 30–35, 35–40, 40–45, and >45 GeV) for both μ^+ and μ^- . The same procedure is applied to both data and MC simulation and scale factors are determined to match the simulation efficiencies to the data.

The measured average tracking efficiency in each η bin varies from 99.6 to 99.9% with a slight inefficiency in the transition regions from the barrel to the endcap segments and at the edge of the tracker system. The ratio of tracking efficiencies for μ^+ and μ^- is consistent with unity within statistical uncertainty. In the transition regions from the DT to the CSC, there is evi-

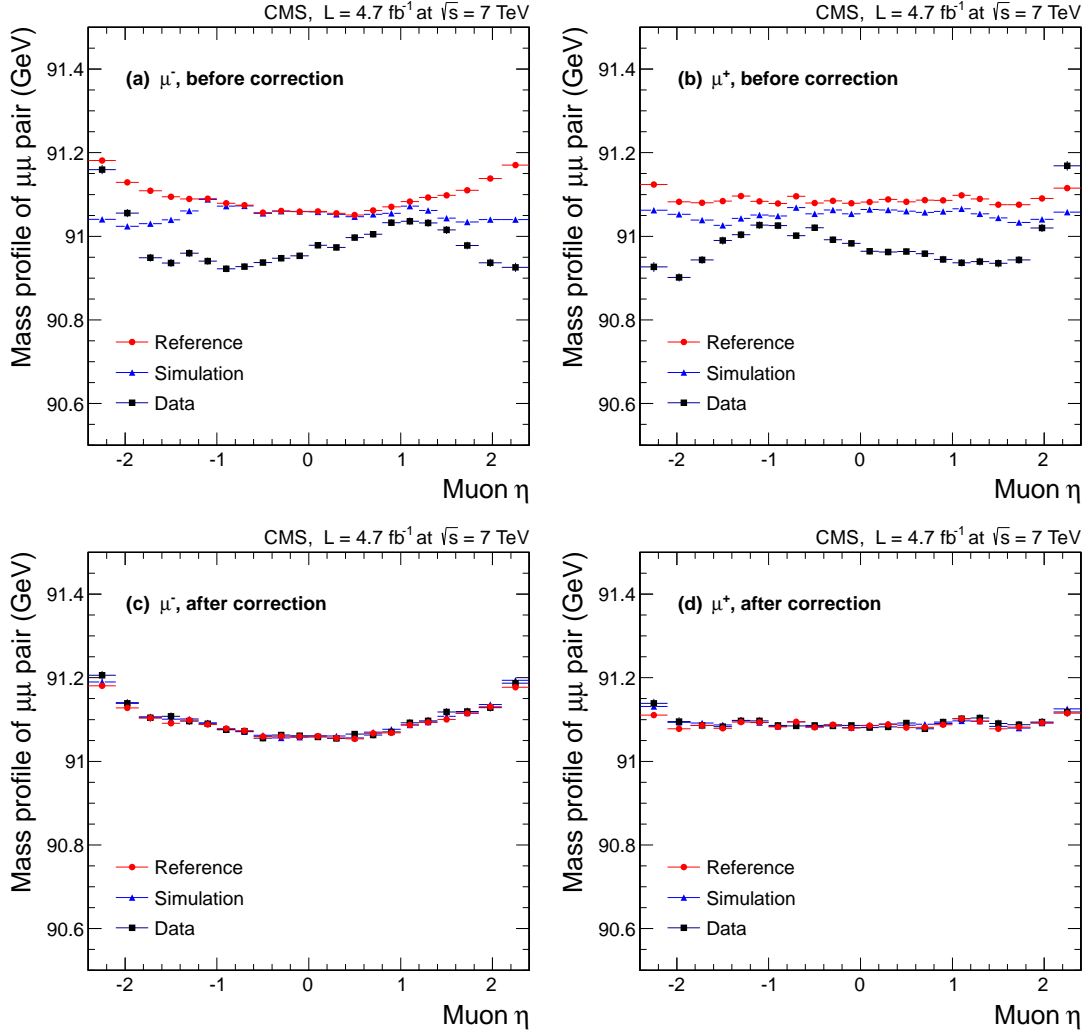


Figure 1: The dimuon mass profile as a function of muon η for μ^- (a, c) and μ^+ (b, d), where (a) and (b) are before the correction and (c) and (d) are after the correction. The mean values of $1/p_T$ spectra at the MC generator level varied by the reconstruction resolution are used as the reference.

dence that the muon offline efficiency has a slight asymmetry between μ^+ and μ^- . The ratio of efficiencies for positively and negatively charged muons differs from unity by up to $1.0 \pm 0.3\%$. The trigger efficiency ratio is also found to differ from unity in some η regions. The maximum deviation is at $\eta > 2.1$ where the efficiency for μ^+ is about $2.0 \pm 0.5\%$ higher than that for μ^- . Figure 2 shows the η distribution for the leading μ^+ and μ^- in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ sample. The dimuon invariant mass is within $60 < m_{\mu\mu} < 120$ GeV. Here, the MC simulation is corrected for muon momentum bias, efficiency, and mismodeling of the Z-boson transverse momentum (\vec{q}_T) before normalizing to the measured data. The η dependence effect in data and MC simulation are in good agreement.

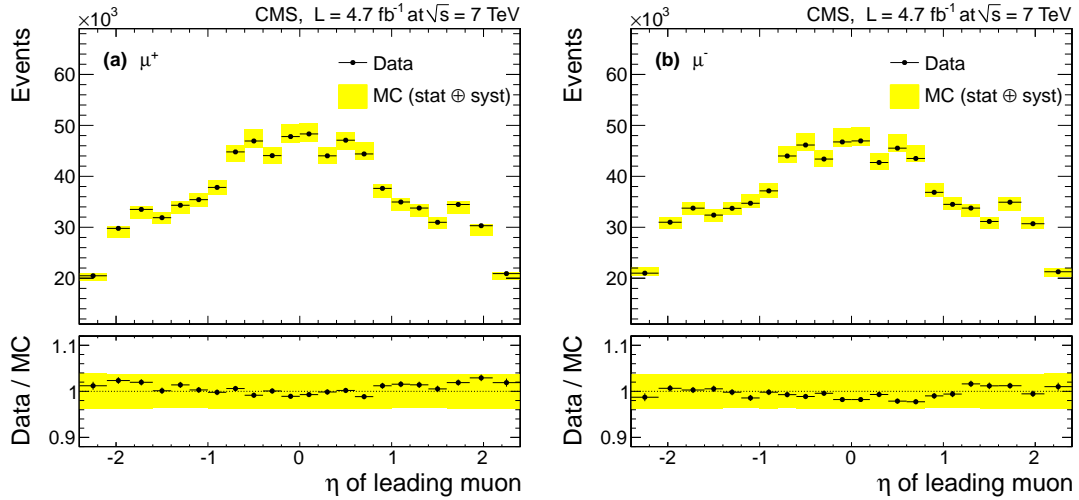


Figure 2: The η distribution of the leading μ^+ (a) and μ^- (b) in $Z/\gamma^* \rightarrow \mu^+\mu^-$ sample. The dimuon invariant mass is within $60 < m_{\mu\mu} < 120$ GeV. The MC simulation is normalized to the data. The light shaded band is the total uncertainty in predicting the $Z/\gamma^* \rightarrow \mu^+\mu^-$ event yields using MC simulation, as described in Section 6.

5 Extraction of the $W \rightarrow \mu\nu$ signal

After the event selection described above, there are a total of 12.9 million $W^+ \rightarrow \mu^+\nu$ and 9.1 million $W^- \rightarrow \mu^-\bar{\nu}$ candidate events. The expected backgrounds from QCD, EW, and $t\bar{t}$ events in the $W \rightarrow \mu\nu$ data sample are about 8%, 8%, and 0.5%, respectively. The background composition varies for different $|\eta|$ bins. The single top-quark and diboson ($WW/WZ/ZZ$) production is less than 0.1% and is neglected.

Binned maximum-likelihood fits of the E_T distributions are performed simultaneously for W^+ and W^- candidate events to extract the W^+ yield (N^{W^+}) and the W^- yield (N^{W^-}) for each $|\eta|$ bin. The likelihood is constructed following the Barlow–Beeston method to take into account the finite MC statistics [29]. The $W \rightarrow \mu\nu$ MC sample is about the same size as the data sample of $W \rightarrow \mu\nu$ candidates. To avoid the large spread of weights introduced by PU weighting, each MC sample is matched to the data PU distribution using an “accept-reject” technique based on the data/MC PU distributions. The accepted MC events are then used to construct the E_T templates used in the fits.

The shapes of the E_T distributions for the $W \rightarrow \mu\nu$ signal and the background contributions are taken directly from MC simulations after correcting for mismodeling of the detector response

and the W -boson \vec{q}_T . The normalizations of the W^+ and W^- signals and the QCD backgrounds are allowed to float. The ratio of the QCD backgrounds for the W^+ and W^- candidate events is fixed using a QCD-enriched data control sample, which was collected using a nonisolated muon trigger. The Drell–Yan production cross section is rescaled using the yields in the Drell–Yan control sample, and the expected Drell–Yan background is normalized using this rescaled normalization factor. The ratio of $W \rightarrow \tau\nu$ to $W \rightarrow \mu\nu$ is determined from a MC simulation, and the $W \rightarrow \tau\nu$ background is normalized to the $W \rightarrow \mu\nu$ candidates in data using this ratio. The $t\bar{t}$ background is normalized to the NLO cross section obtained from MCFM [30–32]. The efficiency in the MC simulation is scaled to match the data efficiency before the extraction of the background normalization factors.

The observed raw charge asymmetry (\mathcal{A}^{raw}) is related to N^{W^+} and N^{W^-} by

$$\mathcal{A}^{\text{raw}} = \frac{N^{W^+} - N^{W^-}}{N^{W^+} + N^{W^-}}. \quad (2)$$

Fixing the ratio of the QCD backgrounds for W^+ and W^- candidate events introduces a correlation between the uncertainties in N^{W^+} and N^{W^-} , which is taken into account when evaluating the uncertainty in \mathcal{A}^{raw} .

The simulation of the \cancel{E}_T in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ MC samples is not in perfect agreement with that observed in data. A small ϕ modulation of the $\vec{\cancel{E}}_T$ distribution is observed in both data and MC simulation, although the phase and amplitude of the modulation differs between data and simulation. The differences in the \cancel{E}_T distributions are due to a variety of sources such as PU, misalignment within subdetectors or between different subsystems, and mismodeling of detector response in simulation. In this analysis, $\vec{\cancel{E}}_T$ is corrected for the muon momentum bias as defined in Section 4. This is done by adding the muon p_T correction vectorially to the $\vec{\cancel{E}}_T$ in the data and MC simulation, respectively. However, a disagreement in the \cancel{E}_T distribution remains at a significant level, resulting in large systematic uncertainty in the measured charge asymmetry. Therefore, the $Z/\gamma^* \rightarrow \mu^+\mu^-$ control sample is used to empirically parametrize the mismodeling to improve the data-MC agreement. We use the “hadronic recoil” technique, which has been previously used in both Tevatron experiments and in CMS [33–35], as described below.

5.1 Definition of the “hadronic recoil”

The “hadronic recoil”, \vec{u} , is defined as a vector sum of transverse momenta of all particle candidates excluding the candidate muon(s). In $Z/\gamma^* \rightarrow \mu^+\mu^-$ events, it is defined to be

$$\vec{u} = -\vec{\cancel{E}}_T - \vec{q}_T, \quad (3)$$

where \vec{q}_T is the transverse momentum of the dimuon system.

In the $Z/\gamma^* \rightarrow \mu^+\mu^-$ event sample, the components of \vec{u} parallel and perpendicular to the Z -boson \vec{q}_T are defined as u_{\parallel} and u_{\perp} , respectively. The mean of u_{\perp} , \bar{u}_{\perp} , is approximately 0. The mean of u_{\parallel} , the average recoil \bar{u}_{\parallel} , is close to the mean of the boson q_T , which is the detector response to the hadronic activity recoiling against the boson \vec{q}_T . The difference between data and simulation in the hadronic recoil distributions seen in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ sample is used to improve the modeling of the \cancel{E}_T in the MC simulation. The procedure of extracting empirical corrections from the $Z/\gamma^* \rightarrow \mu^+\mu^-$ sample and applying them to other physics processes is described below.

5.2 Correction procedure

The first step in the procedure is to correct the \vec{E}_T for both the muon momentum bias described in Section 4, and the ϕ modulation described above. The ϕ modulation of \vec{E}_T is largely due to the fact that collisions, including hard interactions that produce W events as well as PU events, do not occur exactly at the origin of the coordinate system. This modulation can be characterized by a cosine function, $C \cos(\phi - \phi_0)$. The dependence of the amplitude C and phase term ϕ_0 on the number of primary vertices (n) is extracted from the $Z/\gamma^* \rightarrow \mu^+\mu^-$ event sample. This is done by fitting the ϕ -dependent $(u_{||} - \tilde{u}_{||})(q_T)$ profile. Here the $\tilde{u}_{||}(q_T)$ can be parametrized by

$$- \tilde{u}_{||}(q_T) = (c_0 + c_1 q_T) \left(1 + \operatorname{erf}(\alpha q_T^\beta) \right), \quad (4)$$

where c_0 , c_1 , α , and β are floating parameters and $\operatorname{erf}(x)$ is the error function. The amplitude C is found to depend linearly on the number of primary vertices n , while the ϕ_0 is almost independent of PU. The measured C and ϕ_0 distributions in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ data sample and the corresponding MC simulation are different. The ϕ modulation of \vec{E}_T can be removed by adding a 2D vector $(C \cos(\phi_0), C \sin(\phi_0))$ to the \vec{E}_T in each event, with C and ϕ_0 extracted from $Z/\gamma^* \rightarrow \mu^+\mu^-$ events.

The second step is to determine the hadronic recoil in $Z/\gamma^* \rightarrow \mu^+\mu^-$ events. The $\tilde{u}_{||}(q_T)$ is measured as a function of boson q_T in 4 bins of leading jet $|\eta_j|$: [0.0–1.2], [1.2–2.4], [2.4–3.0], and [3.0–5.0]. The jets are formed by clustering particle-flow candidates using the anti- k_T jet clustering algorithm with a distance parameter 0.5 [36]. The identified muon candidates are removed prior to the jet reconstruction. In each $|\eta_j|$ bin, the q_T -dependence of $\tilde{u}_{||}(q_T)$ is parametrized by Eq. (4). The resolutions of $u_{||}$ and u_{\perp} in each boson q_T bin are determined by fitting a Gaussian function to the $u_{||} - \tilde{u}_{||}$ and u_{\perp} distributions, respectively. This is done as a function of the number of primary vertices n . The fitted Gaussian widths as a function of q_T for different numbers of primary vertices are parametrized by the function

$$\sigma(q_T; n) = \sqrt{N_n^2 + S_n^2 q_T}, \quad (5)$$

where N_n , S_n are parameters extracted from the fit. The average recoil and resolutions are extracted for both the $Z/\gamma^* \rightarrow \mu^+\mu^-$ data and the MC simulation.

The last step is to apply the average recoil and resolution extracted from $Z/\gamma^* \rightarrow \mu^+\mu^-$ events to improve the agreement between the data and MC simulation for the \vec{E}_T distribution. As a test, in MC simulation events the $u_{||}$ is shifted by the ratio of $\tilde{u}_{||}$ between data and MC simulation, then parallel and perpendicular resolutions are scaled to match the average values in the data. This is done on an event-by-event basis. The \vec{E}_T is then recalculated using the corrected \vec{u} with Eq. (3). Figure 3 shows the \vec{E}_T and the ϕ of the \vec{E}_T after applying the hadronic recoil correction. The data and MC simulation are in excellent agreement as expected, demonstrating that this empirical correction to \vec{E}_T in the MC simulation works very well for $Z/\gamma^* \rightarrow \mu^+\mu^-$ events. To apply the hadronic recoil correction determined in $Z/\gamma^* \rightarrow \mu^+\mu^-$ events to other MC simulations, such as $W \rightarrow \mu\nu$ events, requires defining a variable equivalent to the boson \vec{q}_T in $Z/\gamma^* \rightarrow \mu^+\mu^-$ events. In $W \rightarrow \mu\nu$ candidate events, the hadronic recoil is defined to be

$$\vec{u} = -\vec{E}_T - \vec{p}_T, \quad (6)$$

where \vec{p}_T is the muon transverse momentum. With a properly defined \vec{q}_T , the hadronic recoil, as defined in Eq. (6), is decomposed into $u_{||}$ and u_{\perp} components relative to the \vec{q}_T . Now the hadronic recoil correction is applied in the same way as in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ MC simulation

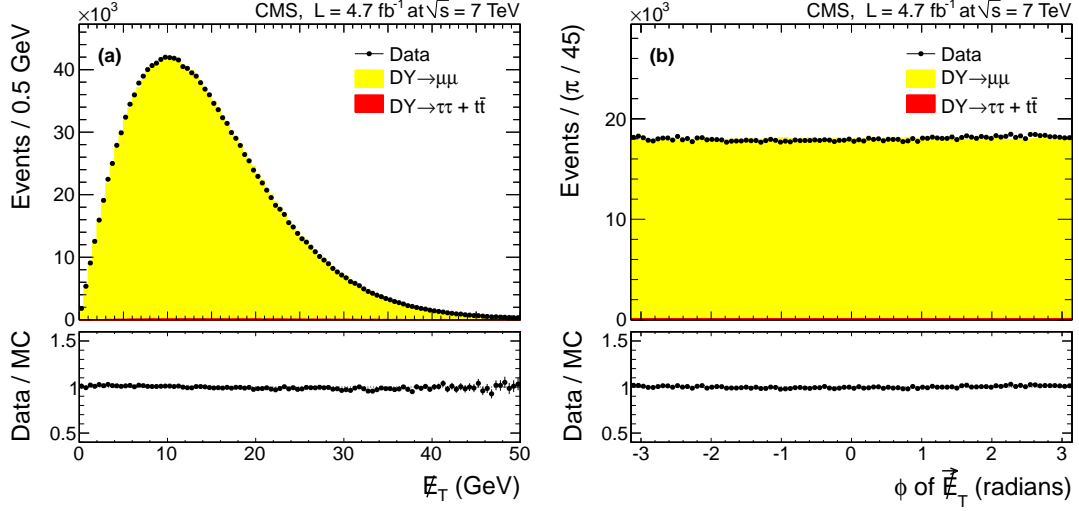


Figure 3: Data to simulation comparison for E_T (a) and ϕ distribution of \vec{E}_T (b) in the Drell–Yan control sample. Here, the hadronic recoil derived from the data was used to correct the MC simulation. The $Z/\gamma^* \rightarrow \tau^+\tau^- + t\bar{t}$ contribution (dark shaded region) in data is normalized to the integrated luminosity of the data sample using a MC simulation, and the normalization of the $Z/\gamma^* \rightarrow \mu^+\mu^-$ MC simulation (light shaded region) is taken as the difference between the data and the estimated $Z/\gamma^* \rightarrow \tau^+\tau^- + t\bar{t}$ contribution. In this data sample, the $Z/\gamma^* \rightarrow \tau^+\tau^- + t\bar{t}$ contribution is negligible.

to correct for the hadronic recoil, and the E_T is re-calculated. For the $W \rightarrow \mu\nu$ MC simulation, the vector sum of the transverse momentum of the reconstructed muon and the generated neutrino is defined to be the \vec{q}_T , while for $W \rightarrow \tau\nu$ events the generated W -boson \vec{q}_T is used. For Drell–Yan background events that pass the Drell–Yan veto, the second muon could fail some of the muon quality selection criteria or fall outside the detector acceptance. The vector sum of the transverse momentum of the generator-level second muon and the reconstructed muon is defined to be the \vec{q}_T . For the QCD background, the \vec{q}_T is defined to be the \vec{p}_T of the reconstructed muon. Figure 4 shows the E_T distribution for the QCD control sample, where events were collected with a prescaled nonisolated muon trigger. Here we select events that fail the isolated muon trigger requirements. We also impose an anti-isolation selection cut $\text{Iso}_{\text{track}}/p_T > 0.1$. For this control sample, which is dominated by the QCD background, data and MC simulation are in very good agreement after the application of the hadronic recoil corrections.

5.3 Extraction of the asymmetry from fits to the missing transverse energy

The $W \rightarrow \mu\nu$ signal is extracted from fits to the E_T distributions of $W \rightarrow \mu\nu$ candidates as shown in Fig. 5 where the muon p_T threshold is 25 GeV. Fits are shown for three $|\eta|$ bins: $0.0 \leq |\eta| < 0.2$, $1.0 \leq |\eta| < 1.2$, and $2.1 \leq |\eta| < 2.4$. The E_T distributions for the $W \rightarrow \mu\nu$ signal and backgrounds are obtained from simulations that are corrected for the hadronic recoil, which is determined from $Z/\gamma^* \rightarrow \mu^+\mu^-$ events. The ratios between the data points and the final fits are shown at the bottom of each panel. Table 1 summarizes the fitted N^{W^+} , N^{W^-} , the correlation between the uncertainties in N^{W^+} and N^{W^-} ($\rho_{(N^{W^+}, N^{W^-})}$), the \mathcal{A}^{raw} (calculated using Eq. (2)), and the χ^2 value of the fit for each $|\eta|$ bin. The χ^2 values show that the fit model describes the data well. The correlation between the uncertainties in N^{W^+} and N^{W^-} is taken into account in the estimated uncertainty of \mathcal{A}^{raw} . This correlation is about 10–15% and varies

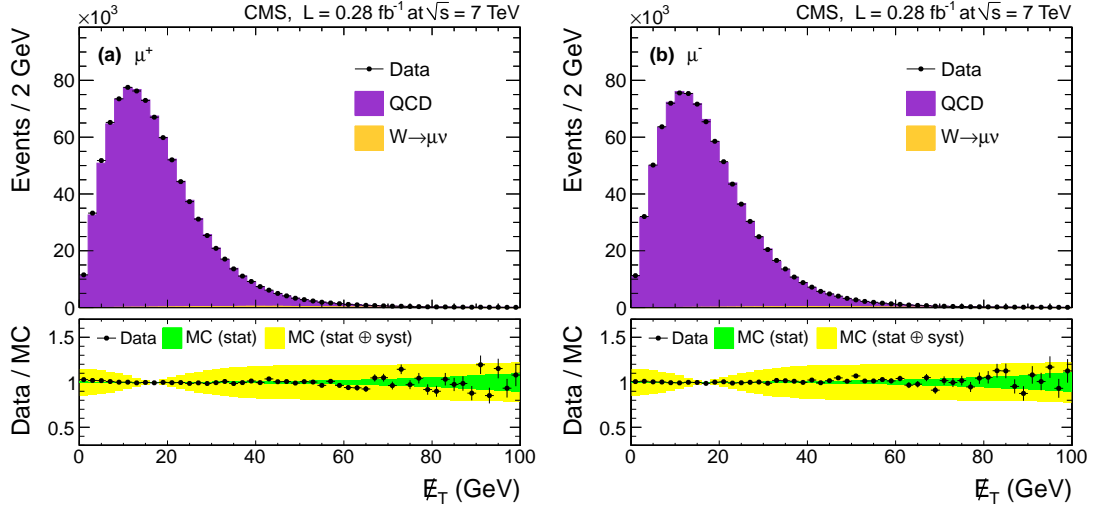


Figure 4: The \cancel{E}_T distribution for μ^+ (a), and μ^- (b) in the data sample dominated by the QCD background. The hadronic recoil derived from data has been used to correct the MC simulation. The $W \rightarrow \mu\nu$ contribution (light shaded region) is normalized to the integrated luminosity of the data sample using a MC simulation, and the normalization of the QCD simulation (dark shaded region) is taken as the difference between the data and the estimated $W \rightarrow \mu\nu$ contribution. The $W \rightarrow \mu\nu$ contribution in this data sample is negligible. The dark shaded band in each ratio plot shows the statistical uncertainty in the QCD MC \cancel{E}_T shape, and the light shaded band shows the total uncertainty, including the systematic uncertainties due to QCD \cancel{E}_T modeling as discussed in Section 6.

from bin to bin. The extracted \mathcal{A}^{raw} is further corrected for possible detector bias as discussed in the sections below.

We also repeat the analysis with a higher muon p_T threshold of 35 GeV. For a higher muon p_T threshold, the background compositions are significantly different. The expected QCD background is reduced to about 1% in the $W \rightarrow \mu\nu$ candidate sample. The $p_T > 35$ GeV sample provides a cross-check of the analysis method and the measurement with this sample enables a direct comparison to the previous measurement of the W boson electron charge asymmetry in [12]. For the higher p_T threshold the theoretical predictions are different due to the different kinematic constraints. The results obtained with a muon p_T threshold of 35 GeV are also summarized in Table 1.

6 Systematic uncertainties and corrections

Here, we investigate the effects of the uncertainties in many backgrounds as well as possible additional corrections to \mathcal{A}^{raw} from detector bias that could result in a difference from the true charge asymmetry ($\mathcal{A}^{\text{true}}$). For the MC simulation $\mathcal{A}^{\text{true}}$ is defined as the asymmetry calculated by taking the muon four-vectors and charge directly from the MC generator.

One possible bias can originate from muon charge misidentification (w), which causes the measured asymmetry to be different from the $\mathcal{A}^{\text{true}}$ by a factor of $1 - 2w$ given a symmetric misidentification rate between μ^+ and μ^- . The muon charge misidentification rate has been studied in detail and shown to have negligible effect on the measured asymmetry [10]. The resolution of muon p_T can introduce a spread of the measured asymmetry from the $\mathcal{A}^{\text{true}}$, and it varies as

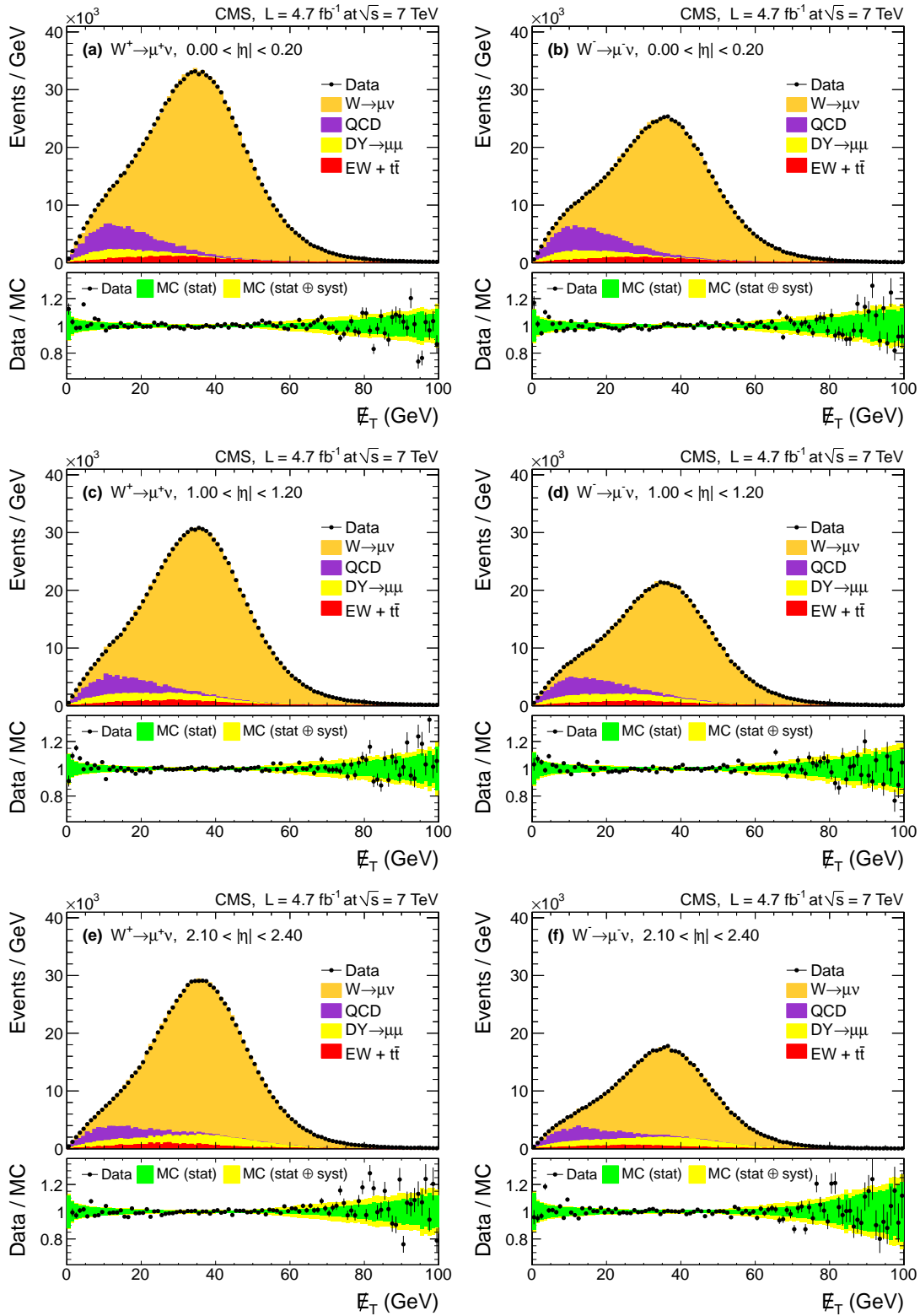


Figure 5: Muon $p_T > 25 \text{ GeV}$ data sample. Examples of the extraction of the $W \rightarrow \mu\nu$ signal from fits to \cancel{E}_T distributions of $W \rightarrow \mu\nu$ candidates in data: $0.0 \leq |\eta| < 0.2$ (a, b), $1.0 \leq |\eta| < 1.2$ (c, d), and $2.1 \leq |\eta| < 2.4$ (e, f). The fits to $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\bar{\nu}$ candidates are in panels (a, c, e) and (b, d, f), respectively. The ratios between the data points and the final fits are shown at the bottom of each panel. The dark shaded band in each ratio plot shows the statistical uncertainty in the shape of the MC \cancel{E}_T distribution, and the light shaded band shows the total uncertainty, including all systematic uncertainties as discussed in Section 6.

Table 1: Summary of the fitted N^{W^+} , N^{W^-} , the correlation between the uncertainties in N^{W^+} and N^{W^-} ($\rho_{(N^{W^+}, N^{W^-})}$), the χ^2 of the fit, and the extracted \mathcal{A}^{raw} for each $|\eta|$ bin. The number of degrees of freedom (n_{doff}) in each fit is 197. Here, $\rho_{(N^{W^+}, N^{W^-})}$ and \mathcal{A}^{raw} are expressed as percentages.

$ \eta $ bin	N^{W^+} (10^3)	N^{W^-} (10^3)	$\rho_{(N^{W^+}, N^{W^-})}$ (%)	χ^2 ($n_{\text{doff}} = 197$)	\mathcal{A}^{raw} (%)
$p_{\text{T}} > 25 \text{ GeV}$					
0.00–0.20	1033.0 ± 1.4	764.9 ± 1.2	14.5	255	14.912 ± 0.096
0.20–0.40	970.2 ± 1.3	713.9 ± 1.2	14.9	190	15.216 ± 0.098
0.40–0.60	1060.3 ± 1.4	771.5 ± 1.2	14.7	220	15.766 ± 0.094
0.60–0.80	1055.1 ± 1.4	752.4 ± 1.2	14.6	213	16.745 ± 0.093
0.80–1.00	935.8 ± 1.3	652.1 ± 1.1	14.5	245	17.866 ± 0.098
1.00–1.20	931.0 ± 1.3	625.4 ± 1.1	13.9	231	19.636 ± 0.099
1.20–1.40	949.0 ± 1.3	621.6 ± 1.1	14.2	209	20.848 ± 0.099
1.40–1.60	957.1 ± 1.3	607.3 ± 1.1	13.7	202	22.365 ± 0.099
1.60–1.85	1131.8 ± 1.4	687.6 ± 1.2	14.7	225	24.417 ± 0.093
1.85–2.10	1113.4 ± 1.4	656.8 ± 1.1	12.9	237	25.797 ± 0.094
2.10–2.40	843.6 ± 1.2	481.3 ± 1.0	11.8	244	27.341 ± 0.106
$p_{\text{T}} > 35 \text{ GeV}$					
0.00–0.20	574.3 ± 1.0	459.7 ± 0.9	18.9	203	11.083 ± 0.116
0.20–0.40	538.9 ± 0.9	428.9 ± 0.9	17.4	202	11.371 ± 0.119
0.40–0.60	588.3 ± 1.0	462.8 ± 0.9	18.5	187	11.935 ± 0.114
0.60–0.80	582.9 ± 1.0	453.7 ± 0.9	18.7	205	12.472 ± 0.114
0.80–1.00	513.7 ± 0.9	392.3 ± 0.8	18.7	218	13.406 ± 0.124
1.00–1.20	509.1 ± 0.9	379.2 ± 0.8	15.7	226	14.620 ± 0.121
1.20–1.40	520.2 ± 0.9	376.9 ± 0.8	16.2	191	15.970 ± 0.123
1.40–1.60	522.7 ± 0.9	370.2 ± 0.8	14.7	195	17.074 ± 0.123
1.60–1.85	614.6 ± 1.0	418.8 ± 0.9	17.5	239	18.945 ± 0.118
1.85–2.10	604.7 ± 1.0	395.8 ± 0.9	15.0	192	20.885 ± 0.123
2.10–2.40	464.3 ± 0.9	288.5 ± 0.8	14.7	234	23.357 ± 0.141

a function of the muon η from 1.5 to 5.0% [27]. The resolution of muon η is several orders of magnitude smaller than the bin widths used in this measurement. The event migration around $p_{\text{T}}\text{-}\eta$ thresholds has a negligible effect on the measured asymmetry. The uncertainty in the muon momentum correction can also contribute an additional systematic uncertainty in the signal estimation, as discussed below. The final-state radiation of photons (FSR) can reduce the muon p_{T} and result in a difference in acceptance between W^+ and W^- for a given muon p_{T} selection. The effect of FSR on the muon charge asymmetry was previously studied using POWHEG MC samples. We found that FSR reduces the asymmetry by about 0.1% in $W \rightarrow \mu\nu$ decays [10].

A difference in the selection efficiency for μ^+ and μ^- can bias the measured charge asymmetry. We can correct for such a difference in the efficiency for μ^+ and μ^- events using the expression

$$\mathcal{A}^{\text{true}} = \mathcal{A}^{\text{raw}} - \frac{1 - (\mathcal{A}^{\text{raw}})^2}{2} \left(r^{W^+/W^-} - 1 \right), \quad (7)$$

where r^{W^+/W^-} is the ratio of the selection efficiency for W^+ and W^- events. The systematic uncertainty in extraction of the $\mathcal{A}^{\text{true}}$ introduced by any difference in efficiencies for the μ^+ and μ^- is discussed below.

The method used to determine the uncertainties in the asymmetry from the muon momentum correction, event selection, and the \cancel{E}_T correction is to generate several hundred or thousand pseudo-experiments and repeat the entire analysis for each pseudo-experiment. The resulting extracted raw charge asymmetries are used to determine corrections to the asymmetry and assign systematic uncertainties.

6.1 Muon efficiency ratio

As discussed previously, the muon offline and trigger efficiencies are measured in 7 bins in p_T and 22 bins in η bins for both μ^+ and μ^- . The offline efficiency ratio between μ^+ and μ^- is very close to unity in most of the detector regions. However, there is evidence that this ratio deviates from unity in the transition regions between the detectors.

We correct for the efficiency bias in the detector using the muon efficiencies extracted from the $Z/\gamma^* \rightarrow \mu^+\mu^-$ data and MC samples. For each $|\eta|$ bin an average W selection efficiency $\epsilon(W^\pm)$ is obtained from the expression

$$\epsilon(W^\pm) = \frac{\sum(k\epsilon_{\text{data}}^\pm(p_T, \eta)/\epsilon_{\text{MC}}^\pm(p_T, \eta))}{\sum(k/\epsilon_{\text{MC}}^\pm(p_T, \eta))}, \quad (8)$$

where $\epsilon_{\text{data}}^\pm(p_T, \eta)$, $\epsilon_{\text{MC}}^\pm(p_T, \eta)$ are total muon efficiencies, k are additional event-by-event weights introduced by W-boson q_T weighting described below, and the sum is over the selected $W \rightarrow \mu\nu$ events. The PU difference between data and MC simulation is corrected using the ‘‘accept-reject’’ technique based on data/MC PU distributions. The efficiency ratio (r^{W^+/W^-}) between $\epsilon(W^+)$ and $\epsilon(W^-)$ is used to correct the \mathcal{A}^{raw} following Eq. (7). All MC samples are corrected for any data/MC efficiency difference.

To estimate the systematic uncertainty due to the muon efficiencies, the muon efficiency values in data and MC simulation are modified according to their errors independently in each p_T - η bin and many pseudo-efficiency tables are generated. In each pseudo-experiment the efficiency values are used to correct the MC simulation and measure the \mathcal{A}^{raw} . The \mathcal{A}^{raw} is further corrected for W selection efficiency ratio r^{W^+/W^-} as described above. The root mean square (RMS) of the resulting asymmetries in each $|\eta|$ bin is treated as the systematic uncertainty originating from the uncertainty in the determination of the ratio of the muon efficiencies. In this study, the variations for different $|\eta|$ bins are completely independent from each other. Therefore, the systematic uncertainties due to the efficiency ratio, the dominant systematic uncertainties, are assumed to have zero correlation between different $|\eta|$ bins.

As a cross-check, Fig. 6 shows a comparison of the measured muon charge asymmetry between positive and negative η regions. This is done by performing an identical measurement in 22 muon η bins. We find that the charge asymmetries for $\eta > 0$ and $\eta < 0$ are in very good agreement with each other.

6.2 Additional corrections and uncertainties

The remaining systematic uncertainties in the extraction of the W lepton charge asymmetry originate from the QCD background, muon momentum correction, the FSR correction, the PDF uncertainty, the normalization of the Drell–Yan background, modeling of the \cancel{E}_T , PU weighting, uncertainty in the integrated luminosity, $t\bar{t}$ and $W \rightarrow \tau\nu$ backgrounds, and W-boson q_T modeling. Among these sources, the QCD background and muon momentum correction cause the largest uncertainties. In the following subsections each source of systematic uncertainty is discussed in detail and correlations between different $|\eta|$ bins are investigated to construct a correlation matrix among the total systematic uncertainties.

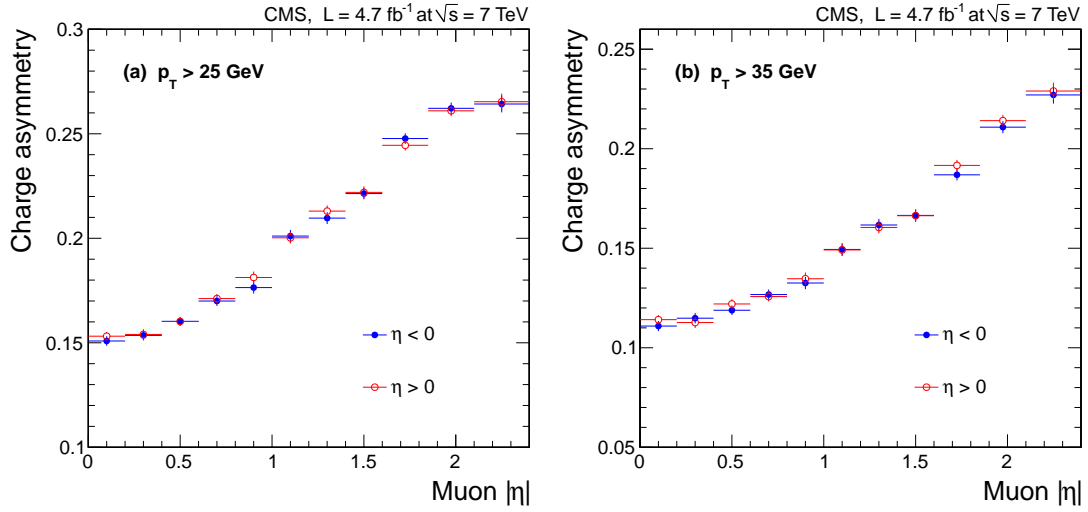


Figure 6: Comparison of the final muon charge asymmetry (\mathcal{A}) extracted for the positive pseudorapidity ($\eta > 0$) and negative pseudorapidity ($\eta < 0$) regions with muon $p_T > 25$ GeV (a) and muon $p_T > 35$ GeV (b) samples. The uncertainties include only the statistical uncertainty from the signal extraction and uncertainty in the determination of the efficiencies for positive and negative muons.

6.2.1 The QCD background

The total QCD background normalization is a parameter in the signal fit. The ratio of the QCD backgrounds in the W^+ and W^- samples is fixed to the ratio observed in the QCD control region. As discussed in Section 5.2, this QCD control sample was collected with a prescaled nonisolated muon trigger. An anti-isolation requirement ($\text{Iso}_{\text{track}}/p_T > 0.1$) has been applied to enhance the QCD contribution. There are two sources of the systematic uncertainties in the QCD background. The first is related to the ratio of the backgrounds in the W^+ and W^- samples (“QCD +/−”), and the second is related to the modeling of the shape of the \cancel{E}_T distribution in QCD events (“QCD shape”).

To evaluate the systematic uncertainties “QCD +/−”, the QCD ratio is varied by ± 5 and $\pm 15\%$ for muon p_T thresholds of 25 and 35 GeV, respectively. The resulting shifts in the \mathcal{A}^{raw} are taken as the uncertainties. For the last $|\eta|$ bin, the variations are 10% (25 GeV) and 20% (35 GeV). These variations of the QCD ratio span the maximum range indicated by the QCD MC simulation. As an additional cross-check, we fix the QCD shape to be the same for μ^+ and μ^- and allow the two QCD normalizations to float in the extraction of the signal. We find that the fitted values for the ratio of the QCD backgrounds for W^+ and W^- are within the uncertainties quoted above. The bin-to-bin correlation of these uncertainties in the asymmetries is assumed to be zero.

The second source of systematic uncertainties is a difference in the shape of the QCD background for W^+ and W^- . The QCD \cancel{E}_T shape is taken from the MC simulation and the recoil correction is applied as discussed in Section 5.2. Two types of variations in the shape of the QCD \cancel{E}_T distribution are considered. First, the shape of the QCD \cancel{E}_T distribution without the hadronic recoil correction is used in the extraction of the signal. This is done in a correlated way for the W^+ and W^- samples. Secondly, the shape of the \cancel{E}_T distribution for the QCD background is varied separately for the W^+ and W^- samples (within the statistical uncertainties) and the resulting shapes are used in the signal extraction. These two contributions to the un-

certainties from the “QCD shape” are then added in quadrature. The bin-to-bin correlation of the systematic uncertainties due to each shape variation is assumed to be 100%.

In total, the systematic uncertainties in the QCD background are comparable to the uncertainties in the muon efficiencies (Table 2).

6.2.2 Muon momentum correction

The muon momentum correction affects both the yields and the shapes of the \cancel{E}_T distributions. To estimate the systematic uncertainty from this source, the muon $1/p_T$ correction parameters in each η - ϕ bin and the muon scale global correction parameters are varied 400 times within their uncertainties. Each time the event yields can be slightly different in both data and MC simulation, and the extraction of the asymmetry is done for each of the 400 cases. The RMS of the measured \mathcal{A}^{raw} variations in each muon $|\eta|$ bin is taken as the systematic uncertainty and the bin-to-bin correlations are assumed to be zero.

The systematic uncertainties resulting from the muon momentum corrections are typically less than 40% of those from the uncertainties in the muon efficiencies for the $p_T > 25$ GeV sample. However, the two uncertainties are comparable for the $p_T > 35$ GeV sample for two reasons: first, the charge dependent bias from the alignment increases with p_T ; second, the Jacobian peak of the $W \rightarrow \mu\nu$ events is close to 35 GeV.

6.2.3 The FSR correction

We studied the impact of the FSR on the muon charge asymmetry using the POWHEG $W \rightarrow \mu\nu$ MC sample. In this sample, FSR is implemented using a similar approach to parton showering and is approximate at the leading order (LO). We compare the muon charge asymmetry before and after FSR, and the difference is found to be within 0.07–0.12% and 0.03–0.11% for muon p_T selections of 25 and 35 GeV, respectively. The central values are not corrected for FSR. However, the full shift in the muon charge asymmetry predicted by the POWHEG MC is taken as an additional systematic uncertainty and the bin-to-bin correlation is assumed to be 100%.

6.2.4 The PDF uncertainty

The PDF4LHC recommendation [37] is followed in the evaluation of the systematic uncertainties originating from uncertainties in the PDFs. The NLO MSTW2008 [2], CT10 [3], and NNPDF2.1 [38] PDF sets are used. All simulated events are weighted to a given PDF set and the overall normalization is allowed to vary. In this way both the uncertainties in the total cross sections, as well as in the shape of the \cancel{E}_T distribution are considered. To estimate the systematic uncertainty resulting from the uncertainties in the CT10 and MSTW2008 PDFs, asymmetric master equations are used [2, 3]. For the CT10, the 90% confidence level (CL) uncertainty is rescaled to 68% CL by dividing by a factor of 1.64485. For the NNPDF2.3 PDF set, the RMS of the \mathcal{A}^{raw} distributions is taken. The half-width of the maximum deviation from combining all three PDF uncertainty bands is taken as the PDF uncertainty. The CT10 error set is used to estimate the bin-to-bin correlations.

The PDF uncertainties are estimated to be about 10% of the total experimental uncertainty. The remaining sources of systematic uncertainties, described in Sections 6.2.5–6.2.10, are smaller and many are negligible.

6.2.5 Drell–Yan background

The $Z/\gamma^* \rightarrow \mu^+\mu^-$ events in the Drell–Yan control region are used to check the Drell–Yan normalization. This is done in bins of dimuon invariant mass: 15–30, 30–40, 40–60, 60–120, 120–150, and >150 GeV. The $Z/\gamma^* \rightarrow \mu^+\mu^-$ MC simulation in each bin is compared to the data yields after correcting the simulation for the data/simulation difference in PU, Z-boson q_T , \cancel{E}_T modeling, and efficiencies. After correcting for the detector bias and physics mismodeling, the MC simulation describes the data well, as shown in Fig. 2 for the dimuon invariant mass between 60 and 120 GeV. The data yield in this mass bin is about 3% higher than the predictions from the next-to-next-to-leading-order (NNLO) cross section as calculated with FEWZ 3.1 [39].

The ratios of data to MC simulation of the $Z/\gamma^* \rightarrow \mu^+\mu^-$ event yields as a function of the dimuon mass are used to rescale the MC prediction of the Drell–Yan background. We take the shift in the \mathcal{A}^{raw} with and without this rescaling as the systematic uncertainty. This and the PDF uncertainties in the $Z/\gamma^* \rightarrow \mu^+\mu^-$ yields are considered as systematic uncertainties due to “Drell–Yan background normalization”. This uncertainty is almost negligible at central $|\eta|$ bins and increases in the forward $|\eta|$ bins. The Drell–Yan background is larger in the forward region because of the lower efficiency of the “Drell–Yan veto” due to less detector coverage. The systematic uncertainties in the Drell–Yan background are assumed to have 100% correlation from bin to bin.

6.2.6 Modeling of missing transverse momentum

To evaluate the systematic uncertainty due to the ϕ modulation of \cancel{E}_T , the correction for the ϕ modulation is removed and the shift in the \mathcal{A}^{raw} is taken as the systematic uncertainty.

The hadronic recoil correction changes the shape of the \cancel{E}_T distribution of all MC samples. To calculate the uncertainties resulting from this source, the average recoil and resolution parameters are varied within their uncertainties, taking into account the correlations between them. This is done 400 times and the RMS of the resulting \mathcal{A}^{raw} variations is taken as systematic uncertainty and bin-to-bin correlations are calculated.

6.2.7 Pileup

Pileup can affect the \cancel{E}_T shapes. To estimate the effect of mismodeling the PU in the simulation, the minimum-bias cross section is varied by $\pm 5\%$ and the PU distributions expected in data are regenerated. The MC simulation is then weighted to match to data and the resulting shift in \mathcal{A}^{raw} is treated as a systematic uncertainty due to the PU. Pileup affects the \cancel{E}_T shapes for all muon η bins in the same direction with a correlation of 100%.

6.2.8 Integrated luminosity

The $Z/\gamma^* \rightarrow \tau^+\tau^-$ and $t\bar{t}$ backgrounds are normalized to the integrated luminosity of the data sample after correcting for the muon efficiency difference between data and MC simulation. The uncertainty in the integrated luminosity is about 2.2% [40]. The normalization of all the MC backgrounds is varied by $\pm 2.2\%$, and the resulting maximum shift in \mathcal{A}^{raw} is taken as the systematic uncertainty in the determination of the luminosity. The bin-to-bin correlations in the measured asymmetries are 100%.

6.2.9 The $t\bar{t}$ and $W \rightarrow \tau\nu$ backgrounds

An additional 15% is assigned as the uncertainty in the theoretical prediction [30–32] of the $t\bar{t}$ cross section. The bin-to-bin correlation of the resulting systematic uncertainty in the asymme-

try is assumed to be 100%.

The $W \rightarrow \tau\nu$ background is normalized to the $W \rightarrow \mu\nu$ yields in data with a ratio obtained from a MC simulation. This ratio is largely determined by the branching fraction of τ decaying to μ . A 2% uncertainty is assigned to the $W \rightarrow \tau\nu$ to $W \rightarrow \mu\nu$ ratio [41]. Here, the bin-to-bin correlations in the measured asymmetries are 100%.

6.2.10 The W-boson q_T modeling

To improve the agreement between data and simulation, the W-boson q_T spectrum is weighted using weight factors that are the ratios of the distribution of boson q_T for $Z/\gamma^* \rightarrow \mu^+\mu^-$ events in data and MC simulation. We make the assumption that the scale factors, which correct the boson q_T distribution in MC simulation so it matches the data, are the same for W and Z events. This assumption is tested using two different sets of MC simulations: one from the POWHEG event generator and the other from MADGRAPH [42]. Here, the MADGRAPH simulation is treated as the “data”, and the ratio of Z-boson q_T between the MADGRAPH and POWHEG simulations is compared to the same ratio in simulated W-boson events. This double ratio is parametrized using an empirical function to smooth the statistical fluctuations, and additional weights are obtained using the fitted function. We weight the POWHEG simulation to be close to the MADGRAPH simulation and measure the asymmetry again. The deviation of \mathcal{A}^{raw} is taken as the systematic uncertainty due to mismodeling of W-boson q_T . The default boson q_T weighting is based on the POWHEG simulation.

6.3 Total systematic uncertainty

Table 2 summarizes the total systematic uncertainties in all $|\eta|$ bins. For comparison, the statistical uncertainty in each $|\eta|$ bin is also shown. The dominant systematic uncertainties are from uncertainties in the muon efficiencies, the QCD background, and the muon momentum correction. The correlation matrix of systematic uncertainty between different $|\eta|$ bins is summarized in Table 3. The correlations between different $|\eta|$ bins are small and do not exceed 37 and 14% for muon p_T thresholds of 25 and 35 GeV, respectively. Much of the correlation is due to the systematic uncertainties in FSR and QCD background. The total covariance matrix, including both statistical and systematic uncertainties, is provided in the Appendix.

7 Results and discussion

The measured asymmetries \mathcal{A} , after all the corrections, are shown in Fig. 7 as a function of muon $|\eta|$ and summarized in Table 4. In Fig. 7 both statistical and systematic uncertainties are included in the error bars. These asymmetries are compared to predictions based on several PDF sets. The theoretical predictions are obtained using the FEWZ 3.1 [39] NLO MC calculation interfaced with the CT10 [3], NNPDF2.3 [43], HERAPDF1.5 [44], MSTW2008 [2], and MSTW2008CPdeut [15] PDF sets. No EW corrections are included in these calculations. The numerical values of the theoretical predictions are shown in Table 4. We cross-check the theoretical predictions using the DYNNLO 1.0 [45, 46] MC tool and the agreement between the FEWZ 3.1 and DYNNLO 1.0 is within 1%. The predictions using the CT10 and HERAPDF1.5 PDF sets are in good agreement with the data. The predictions using the NNPDF2.3 PDF set (which include the previous CMS electron charge asymmetry result and other LHC experimental measurements [43]) are also in good agreement with the data. The predictions using the MSTW2008 PDF set are not in agreement with the data, as seen in our previous analyses [10, 12]. The more recent MSTW2008CPdeut PDF set is a variant of the MSTW2008 PDF set with a more flexible

Table 2: Systematic uncertainties in \mathcal{A} for each $|\eta|$ bin. The statistical uncertainty in each $|\eta|$ bin is also shown for comparison. A detailed description of each systematic uncertainty is given in the text. The values are expressed as percentages, the same as for the asymmetries.

$ \eta $ bin	0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	1.0–1.2	1.2–1.4	1.4–1.6	1.6–1.85	1.85–2.1	2.1–2.4
$p_T > 25 \text{ GeV}$											
Stat. unc.	0.096	0.098	0.094	0.093	0.098	0.099	0.099	0.099	0.093	0.094	0.106
Efficiency	0.111	0.133	0.121	0.122	0.170	0.175	0.170	0.168	0.165	0.175	0.268
QCD $+/-$	0.120	0.113	0.110	0.105	0.102	0.103	0.097	0.104	0.108	0.094	0.183
QCD shape	0.070	0.065	0.065	0.067	0.068	0.069	0.078	0.082	0.092	0.083	0.087
Muon scale	0.045	0.050	0.050	0.049	0.051	0.054	0.054	0.058	0.054	0.054	0.055
FSR	0.074	0.077	0.104	0.109	0.089	0.113	0.107	0.091	0.118	0.087	0.077
PDF	0.028	0.026	0.023	0.025	0.018	0.020	0.027	0.031	0.042	0.050	0.069
Drell–Yan bkg.	0.002	0.001	0.002	0.003	0.000	0.007	0.001	0.013	0.019	0.038	0.046
$E_T \phi$ modul.	0.011	0.009	0.033	0.012	0.029	0.034	0.044	0.045	0.055	0.049	0.038
Recoil	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.003
Pileup	0.017	0.013	0.011	0.005	0.014	0.025	0.022	0.031	0.019	0.028	0.000
Luminosity	0.002	0.003	0.004	0.004	0.006	0.009	0.012	0.017	0.024	0.033	0.040
$t\bar{t}$ bkg.	0.012	0.013	0.012	0.012	0.011	0.011	0.010	0.009	0.008	0.007	0.005
$W \rightarrow \tau\nu$ bkg.	0.026	0.026	0.026	0.026	0.026	0.025	0.025	0.025	0.025	0.025	0.024
$W q_T$	0.003	0.004	0.004	0.005	0.008	0.011	0.008	0.009	0.006	0.003	0.000
Total syst. unc.	0.203	0.212	0.217	0.216	0.238	0.255	0.251	0.250	0.266	0.256	0.364
Total unc.	0.225	0.233	0.236	0.235	0.258	0.274	0.270	0.269	0.282	0.273	0.379
$p_T > 35 \text{ GeV}$											
Stat. unc.	0.116	0.119	0.114	0.114	0.124	0.121	0.123	0.123	0.118	0.123	0.141
Efficiency	0.120	0.138	0.116	0.107	0.159	0.164	0.171	0.176	0.186	0.194	0.325
QCD $+/-$	0.151	0.138	0.135	0.128	0.133	0.118	0.116	0.122	0.137	0.120	0.168
QCD shape	0.030	0.025	0.017	0.023	0.024	0.022	0.018	0.017	0.031	0.031	0.037
Muon scale	0.122	0.135	0.134	0.141	0.146	0.154	0.162	0.170	0.161	0.172	0.189
FSR	0.028	0.050	0.057	0.078	0.022	0.041	0.076	0.055	0.090	0.109	0.105
PDF	0.008	0.008	0.007	0.011	0.012	0.010	0.017	0.022	0.031	0.040	0.058
Drell–Yan bkg.	0.010	0.009	0.009	0.003	0.006	0.010	0.008	0.009	0.009	0.020	0.040
$E_T \phi$ modul.	0.002	0.009	0.010	0.003	0.008	0.028	0.037	0.035	0.022	0.022	0.001
Recoil	0.005	0.006	0.005	0.004	0.005	0.004	0.005	0.004	0.004	0.006	0.008
Pileup	0.015	0.003	0.005	0.018	0.019	0.002	0.007	0.003	0.013	0.014	0.032
Luminosity	0.001	0.002	0.000	0.000	0.000	0.001	0.004	0.010	0.016	0.025	0.039
$t\bar{t}$ bkg.	0.011	0.013	0.012	0.011	0.011	0.010	0.010	0.009	0.007	0.006	0.005
$W \rightarrow \tau\nu$ bkg.	0.013	0.012	0.013	0.012	0.012	0.012	0.011	0.012	0.011	0.011	0.011
$W q_T$	0.004	0.002	0.004	0.004	0.007	0.005	0.006	0.009	0.009	0.001	0.014
Total syst. unc.	0.234	0.245	0.232	0.234	0.258	0.261	0.278	0.283	0.301	0.313	0.436
Total unc.	0.261	0.272	0.259	0.260	0.286	0.288	0.304	0.308	0.323	0.336	0.458

input parametrization and deuteron corrections [15]. This modification has significantly improved the agreement with the CMS data even though they have not included LHC data, as shown in Fig. 7.

Since the per-bin total experimental uncertainties are significantly smaller than the uncertainty in the current PDF parametrizations, this measurement can be used to constrain PDFs in the next generation of PDF sets.

Figure 8 shows a comparison of the measured muon charge asymmetries to the NNLO predictions. The NNLO HERAPDF1.5 PDF is used. The calculations are performed using the FEWZ 3.1 and DYNLO 1.0 MC tools. Both MC simulations give consistent results with agreement at the 1% level. With a p_T threshold of 25 GeV, the NLO and NNLO predictions are very similar. The NNLO predictions are slightly higher in high- $|\eta|$ regions. In the same high- $|\eta|$ region at a p_T threshold of 35 GeV, the NNLO predictions are significantly lower than the NLO prediction. However, they agree well within the quoted PDF uncertainty in the HERAPDF1.5 PDFs.

Figure 9 shows a comparison of this result to the previous CMS electron charge asymmetry

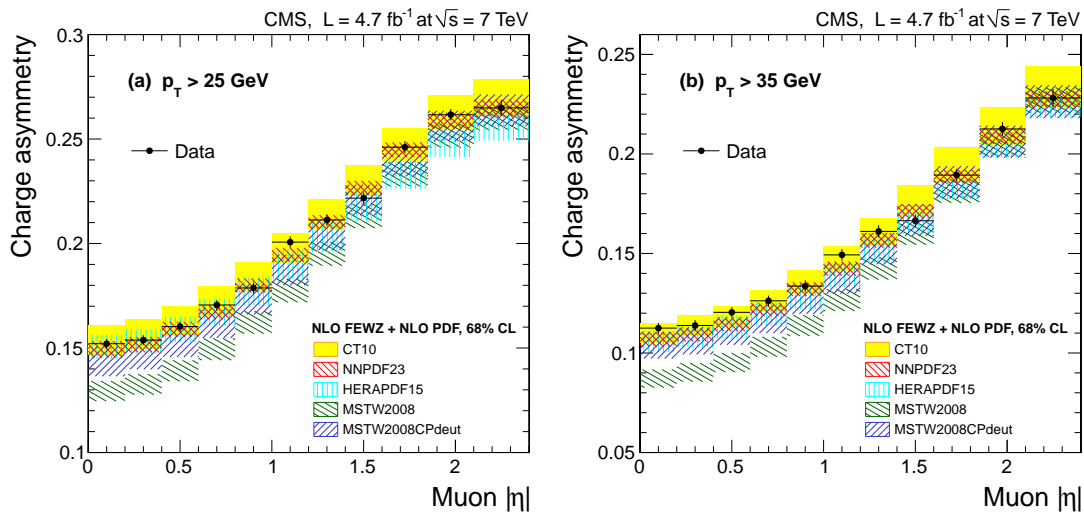


Figure 7: Comparison of the measured muon charge asymmetries to the NLO predictions calculated using the FEWZ 3.1 [39] MC tool interfaced with the NLO CT10 [3], NNPDF2.3 [43], HERAPDF1.5 [44], MSTW2008 [2], and MSTW2008CPdeut [15] PDF sets. No EW corrections have been considered in these predictions. Results for muon $p_T > 25$ and >35 GeV are shown in panels (a) and (b), respectively. The vertical error bars on data points include both statistical and systematic uncertainties. The data points are shown at the center of each $|\eta|$ bin. The theoretical predictions are calculated using the FEWZ 3.1 [39] MC tool. The PDF uncertainty for each PDF set is shown by the shaded (or hatched) band and corresponds to 68% CL.

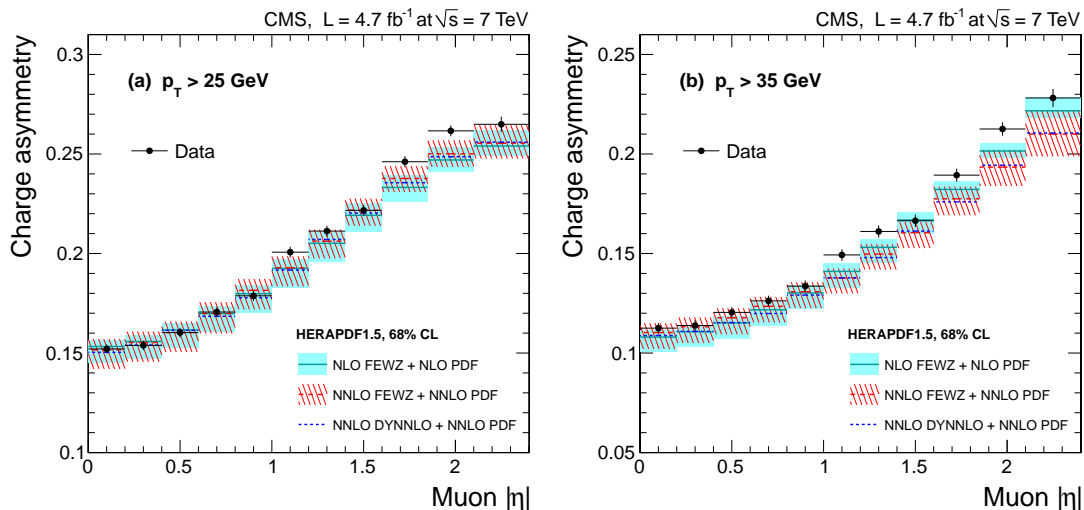


Figure 8: Comparison of the measured muon charge asymmetries to the NNLO predictions for muon $p_T > 25$ (a) and muon $p_T > 35$ GeV (b). The NNLO HERAPDF1.5 [44] PDF has been used in the NNLO calculations. The calculations are performed using both the FEWZ 3.1 [39] and DYNLLO 1.0 [45, 46] MC tools. The NLO prediction based on FEWZ 3.1 is also shown here. The HERAPDF1.5 PDF uncertainties are shown by the shaded (NLO) and hatched (NNLO) bands.

Table 3: Correlation matrix of systematic uncertainties between different $|\eta|$ bins. All systematic uncertainties are treated as additive. The values are expressed as percentages.

$ \eta $ bin	0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	1.0–1.2	1.2–1.4	1.4–1.6	1.6–1.85	1.85–2.1	2.1–2.4
$p_T > 25 \text{ GeV}$											
0.00–0.20	100.0	28.1	32.4	32.9	27.1	29.0	29.5	28.0	30.5	26.1	16.7
0.20–0.40		100.0	30.7	31.4	25.6	27.5	27.9	26.3	28.9	24.5	15.8
0.40–0.60			100.0	37.4	30.9	33.8	34.5	32.1	36.1	30.3	19.3
0.60–0.80				100.0	31.1	34.0	34.4	32.0	36.3	30.4	20.0
0.80–1.00					100.0	28.5	29.5	28.0	31.2	26.9	17.3
1.00–1.20						100.0	32.6	31.1	34.8	30.2	19.3
1.20–1.40							100.0	32.8	36.9	32.2	20.8
1.40–1.60								100.0	36.0	32.7	21.3
1.60–1.85									100.0	37.1	24.9
1.85–2.10										100.0	24.4
2.10–2.40											100.0
$p_T > 35 \text{ GeV}$											
0.00–0.20	100.0	4.6	4.8	6.4	3.4	3.6	4.7	3.4	5.4	5.8	4.3
0.20–0.40		100.0	6.4	8.5	3.3	4.3	6.3	4.4	7.2	8.0	5.8
0.40–0.60			100.0	9.8	3.8	5.6	8.4	6.2	8.9	9.9	6.6
0.60–0.80				100.0	5.1	6.9	10.7	7.8	11.9	13.5	9.7
0.80–1.00					100.0	3.2	4.2	3.3	4.7	5.0	3.6
1.00–1.20						100.0	7.0	5.4	7.0	7.5	4.7
1.20–1.40							100.0	8.1	10.8	12.0	7.8
1.40–1.60								100.0	8.8	9.9	6.7
1.60–1.85									100.0	14.2	10.3
1.85–2.10										100.0	12.6
2.10–2.40											100.0

measurement extracted from part of the 2011 CMS data [12]. For most of the data points, the agreement is within one standard deviation. The electron charge asymmetry uses a statistically independent data sample. A combination of both results can be used to improve the global PDF fits. The correlation between the electron charge asymmetry and this result is expected to be small. The completely correlated systematic sources of uncertainty include the luminosity measurement, $t\bar{t}$ background, $W \rightarrow \tau\nu$ background, and PDF uncertainty.

The theoretical predictions for the lepton charge asymmetry are given for the kinematic region specified by the lepton p_T threshold. The p_T distribution of the W boson affects the acceptance, and hence, the predicted charge asymmetry. However, the effect on W^+ and W^- is largely correlated. Therefore, the impact on the lepton charge asymmetry measurement mostly cancels. Figure 10 shows the comparison of these results to the NLO CT10 PDF predictions based on the FEWZ 3.1 and RESBOS [47–50]. RESBOS does a resummation in boson q_T at approximate next-to-next-to-leading logarithm which yields a more realistic description of boson q_T than a fixed-order calculation such as the FEWZ 3.1. The difference between the FEWZ 3.1 and RESBOS predictions is negligible and our measurement, however precise, is not sensitive to the difference.

8 The QCD analysis of HERA and CMS results of W-boson production

The main objective of the QCD analysis presented in this section is to exploit the constraining power and the interplay of the muon charge asymmetry measurements, presented in this paper, and the recent measurements of $W + \text{charm}$ production at CMS [18] to determine the PDFs of the proton. These two data sets, together with the combined HERA inclusive cross section measurements [19], are used in an NLO perturbative QCD (pQCD) analysis.

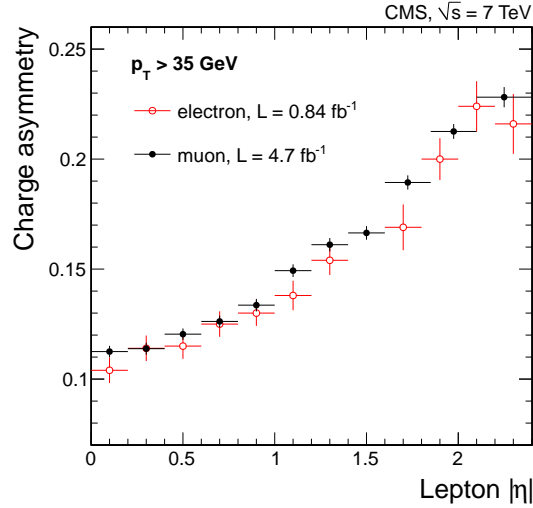


Figure 9: Comparison of this measurement to the previous CMS electron charge asymmetry result [12]. Results are shown for lepton $p_T > 35$ GeV.

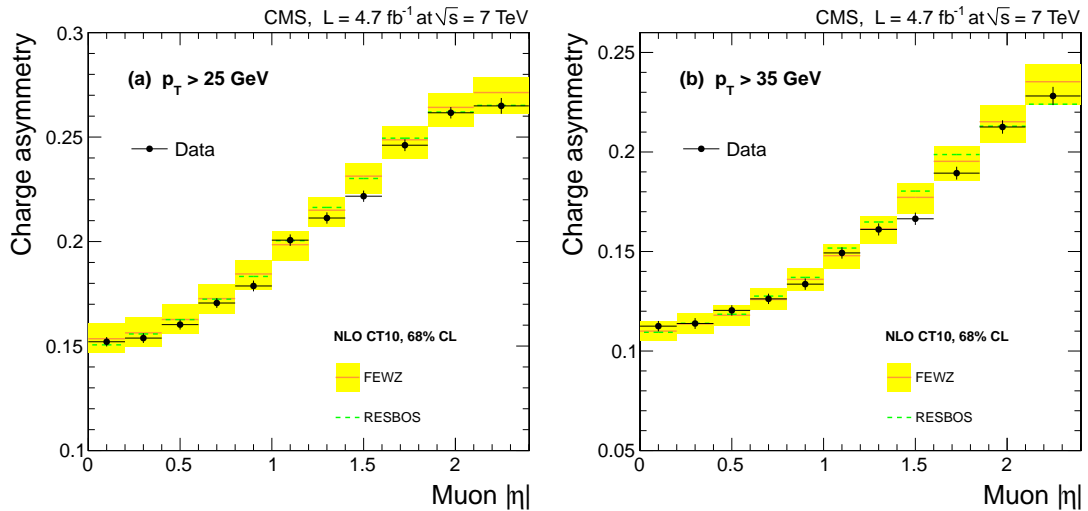


Figure 10: Comparison of the measured muon charge asymmetry to theoretical predictions based on the FEWZ 3.1 [39] and RESBOS [47–50] MC tools. The NLO CT10 PDF is used in both predictions. Results are shown for muon $p_T > 25$ (a) and muon $p_T > 35$ GeV (b). The CT10 PDF uncertainty is shown by the shaded bands.

Table 4: Summary of the final results for muon charge asymmetry \mathcal{A} . The first uncertainty is statistical and the second is systematic. The theoretical predictions are obtained using the FEWZ 3.1 [39] MC tool interfaced with the NLO CT10 [3], NNPDF2.3 [43], HERAPDF1.5 [44], and MSTW2008CPdeut [15] PDF sets. The PDF uncertainty is at 68% CL. For each $|\eta|$ bin, the theoretical prediction is calculated using the averaged differential cross sections for positively and negatively charged leptons. The numerical precision of the theoretical predictions is less than 10% of the statistical uncertainties of the measurements. The values are expressed as percentages.

$ \eta $	$\mathcal{A} (\pm (\text{stat.}) \pm (\text{syst.}))$	CT10	NNPDF2.3	HERAPDF1.5	MSTW2008-CP-deut
$p_T > 25 \text{ GeV}$					
0.00–0.20	$15.21 \pm 0.10 \pm 0.20$	$15.35^{+0.74}_{-0.68}$	14.94 ± 0.39	$15.33^{+0.30}_{-0.84}$	$14.34^{+0.75}_{-0.69}$
0.20–0.40	$15.38 \pm 0.10 \pm 0.21$	$15.63^{+0.73}_{-0.69}$	15.16 ± 0.37	$15.58^{+0.32}_{-0.85}$	$14.67^{+0.75}_{-0.69}$
0.40–0.60	$16.03 \pm 0.09 \pm 0.22$	$16.27^{+0.71}_{-0.70}$	15.90 ± 0.36	$16.16^{+0.34}_{-0.88}$	$15.27^{+0.75}_{-0.70}$
0.60–0.80	$17.06 \pm 0.09 \pm 0.22$	$17.27^{+0.68}_{-0.71}$	16.71 ± 0.34	$16.98^{+0.37}_{-0.91}$	$16.19^{+0.74}_{-0.71}$
0.80–1.00	$17.88 \pm 0.10 \pm 0.24$	$18.45^{+0.66}_{-0.74}$	17.99 ± 0.33	$17.98^{+0.42}_{-0.94}$	$17.33^{+0.74}_{-0.73}$
1.00–1.20	$20.07 \pm 0.10 \pm 0.26$	$19.85^{+0.64}_{-0.76}$	19.46 ± 0.33	$19.25^{+0.48}_{-0.95}$	$18.74^{+0.73}_{-0.74}$
1.20–1.40	$21.13 \pm 0.10 \pm 0.25$	$21.50^{+0.63}_{-0.80}$	21.03 ± 0.33	$20.51^{+0.54}_{-0.92}$	$20.45^{+0.72}_{-0.76}$
1.40–1.60	$22.17 \pm 0.10 \pm 0.25$	$23.13^{+0.64}_{-0.84}$	22.66 ± 0.34	$21.92^{+0.59}_{-0.84}$	$22.12^{+0.70}_{-0.78}$
1.60–1.85	$24.61 \pm 0.09 \pm 0.27$	$24.87^{+0.65}_{-0.89}$	24.49 ± 0.35	$23.32^{+0.63}_{-0.70}$	$24.01^{+0.68}_{-0.79}$
1.85–2.10	$26.16 \pm 0.09 \pm 0.26$	$26.42^{+0.67}_{-0.95}$	25.88 ± 0.38	$24.70^{+0.65}_{-0.57}$	$25.70^{+0.65}_{-0.81}$
2.10–2.40	$26.49 \pm 0.11 \pm 0.36$	$27.13^{+0.74}_{-1.03}$	26.46 ± 0.42	$25.40^{+0.81}_{-0.48}$	$26.48^{+0.65}_{-0.87}$
$p_T > 35 \text{ GeV}$					
0.00–0.20	$11.25 \pm 0.12 \pm 0.23$	$11.00^{+0.52}_{-0.48}$	10.68 ± 0.37	$10.80^{+0.32}_{-0.76}$	$10.39^{+0.67}_{-0.67}$
0.20–0.40	$11.38 \pm 0.12 \pm 0.24$	$11.36^{+0.52}_{-0.49}$	10.91 ± 0.33	$11.07^{+0.33}_{-0.77}$	$10.61^{+0.68}_{-0.68}$
0.40–0.60	$12.04 \pm 0.11 \pm 0.23$	$11.80^{+0.52}_{-0.50}$	11.40 ± 0.31	$11.51^{+0.34}_{-0.79}$	$11.10^{+0.70}_{-0.69}$
0.60–0.80	$12.62 \pm 0.11 \pm 0.23$	$12.59^{+0.53}_{-0.53}$	12.18 ± 0.33	$12.17^{+0.36}_{-0.80}$	$11.71^{+0.72}_{-0.71}$
0.80–1.00	$13.36 \pm 0.12 \pm 0.26$	$13.60^{+0.55}_{-0.58}$	13.21 ± 0.35	$13.02^{+0.37}_{-0.82}$	$12.70^{+0.74}_{-0.74}$
1.00–1.20	$14.93 \pm 0.12 \pm 0.26$	$14.79^{+0.59}_{-0.64}$	14.24 ± 0.36	$14.10^{+0.40}_{-0.81}$	$13.75^{+0.77}_{-0.77}$
1.20–1.40	$16.11 \pm 0.12 \pm 0.28$	$16.14^{+0.64}_{-0.73}$	15.65 ± 0.36	$15.31^{+0.41}_{-0.77}$	$15.24^{+0.79}_{-0.79}$
1.40–1.60	$16.64 \pm 0.12 \pm 0.28$	$17.72^{+0.70}_{-0.83}$	17.11 ± 0.36	$16.68^{+0.40}_{-0.68}$	$16.69^{+0.79}_{-0.82}$
1.60–1.85	$18.94 \pm 0.12 \pm 0.30$	$19.53^{+0.77}_{-0.94}$	18.87 ± 0.36	$18.22^{+0.40}_{-0.51}$	$18.62^{+0.77}_{-0.86}$
1.85–2.10	$21.26 \pm 0.12 \pm 0.31$	$21.52^{+0.82}_{-1.06}$	20.89 ± 0.38	$20.15^{+0.41}_{-0.32}$	$20.71^{+0.71}_{-0.90}$
2.10–2.40	$22.81 \pm 0.14 \pm 0.44$	$23.53^{+0.86}_{-1.17}$	22.73 ± 0.42	$22.17^{+0.71}_{-0.33}$	$22.79^{+0.66}_{-0.99}$

Renormalization group equations, formulated in terms of DGLAP evolution equations [51–56], predict the dependence of the PDFs on the energy scale Q of the process in pQCD. The dependence on the partonic fraction x of the proton momentum cannot be derived from first principles and must be constrained by experimental measurements. Deep inelastic lepton-proton scattering (DIS) experiments cover a broad range of the (x, Q^2) kinematic plane. The region of small and intermediate x is probed primarily by the precise data of HERA, which impose the tightest constraints on the existing PDFs. However, some details of flavor composition, in particular the light-sea-quark content and the strange-quark distribution of the proton, are still poorly known. Measurements of the W- and Z-boson production cross sections in proton-(anti)proton collisions are sensitive to the light-quark distributions, and the constraining power of the W-boson measurements is applied in this analysis.

The muon charge asymmetry measurements probe the valence-quark distribution in the kinematic range $10^{-3} \leq x \leq 10^{-1}$ and have indirect sensitivity to the strange-quark distribution. The measurements of the total and differential cross sections of W + charm production

have the potential to access the strange-quark distribution directly through the LO process $g + s \rightarrow W + c$. This reaction was proposed as a way to determine the strange-quark and antiquark distributions [57–59].

Before the LHC era, constraints on the strange-quark distribution were obtained from semi-inclusive charged-current scattering at the NuTeV [60, 61] and CCFR [62] experiments. Dimuon production in neutrino-nucleus reactions is sensitive to strangeness at LO in QCD in reactions such as $W^+ + s \rightarrow c$. These measurements probe the (anti)strange-quark density at $x \approx 10^{-1}$ and Q^2 of approximately 10 GeV^2 , but their interpretation is complicated by nuclear corrections and uncertainties in the charm-quark fragmentation function. The NOMAD Collaboration reported a recent determination of the strange-quark suppression factor

$$\kappa_s(Q^2) = \frac{\int_0^1 x [\bar{s}(x, Q^2) + s(x, Q^2)] dx}{\int_0^1 x [\bar{u}(x, Q^2) + \bar{d}(x, Q^2)] dx}, \quad (9)$$

where the value $\kappa_s(Q^2 = 20 \text{ GeV}^2) = 0.591 \pm 0.019$ is determined at NNLO by using dimuon production [63]. The measurements of semi-inclusive hadron production on a deuteron target at HERMES [64] have been recently reevaluated [65] to obtain the x dependence of the strange-quark distribution at LO at an average $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$. In that analysis the strange-quark distribution is found to vanish above $x = 0.1$, but this result depends strongly on the assumptions of the kaon fragmentation function.

In a recent analysis by the ATLAS Collaboration [66], the inclusive cross section measurements of W - and Z -boson production were used in conjunction with DIS inclusive data from HERA. The result supports the hypothesis of a symmetric composition of the light-quark sea in the kinematic region probed, i.e., $\bar{s} = \bar{d}$.

The LHC measurements of associated production of W bosons and charm quarks probe the strange-quark distribution in the kinematic region of $x \approx 0.012$ at the scale $Q^2 = m_W^2$. The cross sections for this process were recently measured by the CMS Collaboration [18] at a center-of-mass energy $\sqrt{s} = 7 \text{ TeV}$ with a total integrated luminosity of 5 fb^{-1} . The results of the QCD analysis presented here use the absolute differential cross sections of $W + \text{charm}$ production, measured in bins of the pseudorapidity of the lepton from the W decay, for transverse momenta larger than 35 GeV .

8.1 Details of the QCD analysis

The NLO QCD analysis is based on the inclusive DIS data [19] from HERA, measurements of the muon charge asymmetry in W production for $p_T > 25 \text{ GeV}$, and measurements of associated $W + \text{charm}$ production [18]. The treatment of experimental uncertainties for the HERA data follows the prescription of HERAPDF1.0 [19]. The correlations of the experimental uncertainties for the muon charge asymmetry and $W + \text{charm}$ data are taken into account.

The theory predictions for the muon charge asymmetry and $W + \text{charm}$ production are calculated at NLO by using the MCFM program [30, 31], which is interfaced to APPLGRID [67].

The open source QCD fit framework for PDF determination herafitter [19, 68, 69] is used and the partons are evolved by using the QCDNUM program [70]. The TR' [2, 71] general mass variable flavor number (GMVFN) scheme is used for the treatment of heavy-quark contributions with the following conditions: (i) heavy-quark masses are chosen as $m_c = 1.4 \text{ GeV}$ and $m_b = 4.75 \text{ GeV}$, (ii) renormalization and factorization scales are set to $\mu_r = \mu_f = Q$, and (iii) the strong coupling constant is set to $\alpha_s(m_Z) = 0.1176$.

The Q^2 range of HERA data is restricted to $Q^2 \geq Q_{\min}^2 = 3.5 \text{ GeV}^2$ to assure the applicability of pQCD over the kinematic range of the fit. The procedure for the determination of the PDFs follows the approach used in the HERAPDF1.0 QCD fit [19].

The following independent combination of parton distributions are chosen in the fit procedure at the initial scale of the QCD evolution $Q_0^2 = 1.9 \text{ GeV}^2$: $xu_v(x)$, $xd_v(x)$, $xg(x)$ and $x\bar{U}(x)$, $x\bar{D}(x)$ where $x\bar{U}(x) = x\bar{u}(x)$, $x\bar{D}(x) = x\bar{d}(x) + x\bar{s}(x)$. At Q_0 , the parton distributions are represented by

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2), \quad (10)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}, \quad (11)$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}}, \quad (12)$$

$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}}, \quad (13)$$

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} + A'_g x^{B'_g} (1-x)^{C'_g}. \quad (14)$$

The normalization parameters A_{u_v} , A_{d_v} , A_g are determined by the QCD sum rules, the B parameter is responsible for small- x behavior of the PDFs, and the parameter C describes the shape of the distribution as $x \rightarrow 1$. A flexible form for the gluon distribution is adopted here, where the choice of $C'_g = 25$ is motivated by the approach of the MSTW group [2, 71].

Two types of analyses are made. The first is denoted as “fixed- s fit” and is performed by fitting 13 parameters in Eqs. (10-14) to analyze the impact of the muon charge asymmetry measurements on the valence-quark distributions. Additional constraints $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$ are imposed with f_s being the strangeness fraction, $f_s = \bar{s}/(\bar{d} + \bar{s})$, which is fixed to $f_s = 0.31 \pm 0.08$ as in Ref. [2].

The second analysis is denoted as “free- s fit”, in which the interplay between the muon charge asymmetry measurements and $W + \text{charm}$ production data is analyzed. The strange-quark distribution is determined by fitting 15 parameters in Eqs. (10-14). Here, instead of Eq. (13) \bar{d} and \bar{s} are fitted separately by using the functional forms

$$x\bar{d}(x) = A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}}, \quad (15)$$

$$x\bar{s}(x) = A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}}. \quad (16)$$

Additional constraints $A_{\bar{u}} = A_{\bar{d}}$ and $B_{\bar{u}} = B_{\bar{d}}$ are applied to ensure the same normalization for \bar{u} and \bar{d} densities at $x \rightarrow 0$. The strange-antiquark parameter $B_{\bar{s}}$ is set equal to $B_{\bar{d}}$, while $A_{\bar{s}}$ and $C_{\bar{s}}$ are treated as free parameters of the fit, assuming $x\bar{s} = x\bar{s}$. This parametrization cannot be applied to HERA DIS data alone, because those data do not have sufficient sensitivity to the strange-quark distribution.

8.2 The PDF uncertainties

The PDF uncertainties are estimated according to the general approach of HERAPDF1.0 [19] in which experimental, model, and parametrization uncertainties are taken into account. A tolerance criterion of $\Delta\chi^2 = 1$ is adopted for defining the experimental uncertainties that originate from the measurements included in the analysis. Model uncertainties arise from the variations in the values assumed for the heavy-quark masses m_b , m_c with $4.3 \leq m_b \leq 5 \text{ GeV}$, $1.35 \leq m_c \leq 1.65 \text{ GeV}$, and the value of Q_{\min}^2 imposed on the HERA data, which is varied in the interval $2.5 \leq Q_{\min}^2 \leq 5.0 \text{ GeV}^2$. The parametrization uncertainty is estimated similarly to the HERAPDF1.0 procedure: for all parton densities, additional parameters are added

one by one in the functional form of the parametrizations such that Eqs. (10-13) are generalized to $A x^B (1-x)^C (1+Dx)$ or $A x^B (1-x)^C (1+Dx+Ex^2)$. In the free-s fit, in addition, the parameters $B_{\bar{s}}$ and $B_{\bar{d}}$ are decoupled. Furthermore, the starting scale is varied within $1.5 \leq Q_0^2 \leq 2.5 \text{ GeV}^2$. The parametrization uncertainty is constructed as an envelope built from the maximal differences between the PDFs resulting from all the parametrization variations and the central fit at each x value. The total PDF uncertainty is obtained by adding experimental, model, and parametrization uncertainties in quadrature. In the following, the quoted uncertainties correspond to 68% CL.

8.3 Results of the QCD analysis

The muon charge asymmetry measurements, together with HERA DIS cross section data, improve the precision of the valence quarks over the entire x range in the fixed-s fit. This is illustrated in Fig. 11, where the u and d valence-quark distributions are shown at the scale relevant for the W-boson production, $Q^2 = m_W^2$. The results at $Q^2 = 1.9 \text{ GeV}^2$ can be found in supplemental material. A change in the shapes of the light-quark distributions within the total uncertainties is observed. The details of the effect on the experimental PDF uncertainty of u valence, d valence, and d/u distributions are also given in supplemental material.

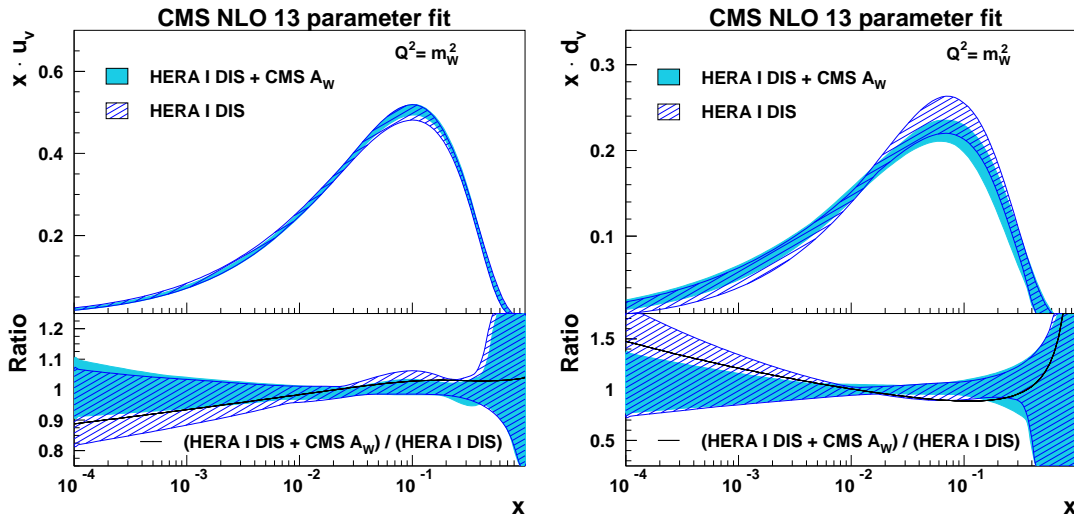


Figure 11: Distributions of u valence (left) and d valence (right) quarks as functions of x at the scale $Q^2 = m_W^2$. The results of the 13-parameter fixed-s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The total PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

In the next step of the analysis, the CMS W + charm measurements are used together with the HERA DIS data and the CMS muon charge asymmetry. Since both CMS W-boson production measurements are sensitive to the strange-quark distribution, a free-s fit can be performed. The advantage of including these two CMS data sets in the 15-parameter fit occurs because the d-quark distribution is significantly constrained by the muon charge asymmetry data, while the strange-quark distribution is directly probed by the associated W + charm production measurements. In the free-s fit, the strange-quark distribution $s(x, Q^2)$, and the strange-quark fraction $R_s(x, Q^2) = (s + \bar{s}) / (\bar{u} + \bar{d})$ are determined. The global and partial χ^2 values for each data set are listed in Table 5, where the χ^2 values illustrate a general agreement among all the data sets.

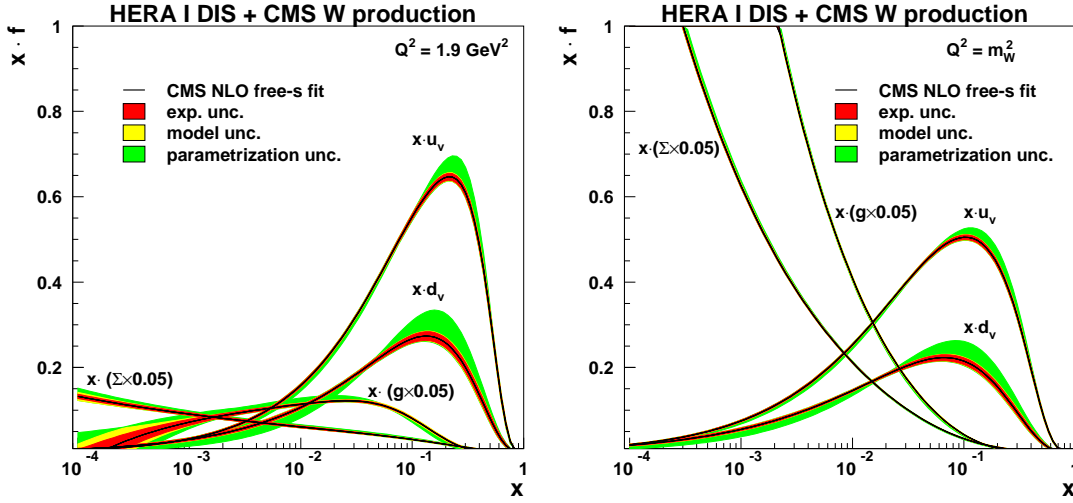


Figure 12: Parton distribution functions, shown as functions of x , obtained by using HERA DIS data and CMS measurements of W-boson production in the free-s NLO QCD analysis. Gluon, valence, and sea distributions are presented at the starting scale $Q_0^2 = 1.9 \text{ GeV}^2$ of the PDF evolution (left) and the mass squared of the W boson (right). The sea distribution is defined as $\Sigma = 2 \cdot (\bar{u} + \bar{d} + \bar{s})$. The full band represents the total uncertainty. The individual contributions from the experimental, model, and parametrization uncertainties are represented by the bands of different shades. The gluon and sea distributions are scaled down by a factor of 20.

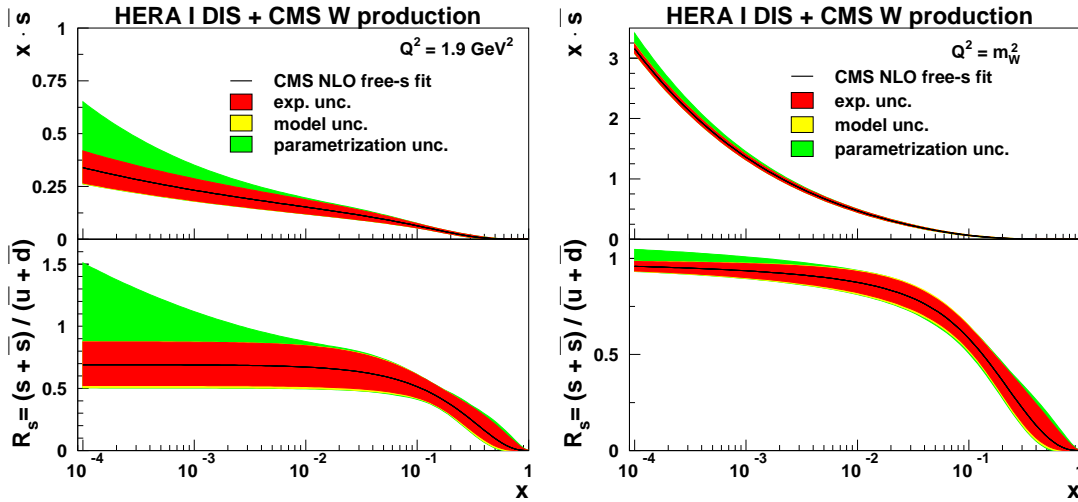


Figure 13: Antistrange-quark distribution $\bar{s}(x, Q)$ and the ratio $R_s(x, Q)$, obtained in the QCD analysis of HERA and CMS data, shown as functions of x at the scale $Q^2 = 1.9 \text{ GeV}^2$ (left) and $Q^2 = m_W^2$ (right). The full band represents the total uncertainty. The individual contributions from the experimental, model, and parametrization uncertainties are represented by the bands of different shades.

Table 5: Global χ^2/n_{dof} and partial χ^2 per number of data points n_{dp} for the data sets used in the 15-parameter QCD analysis.

Data sets	Global χ^2/n_{dof}	Partial χ^2/n_{dp}
DIS, $\frac{d\sigma_{W+c}}{d\eta'}$, $\mathcal{A}(\eta_\mu)$	598/593	
NC cross section HERA I H1+ZEUS e^-p		107/145
NC cross section HERA I H1+ZEUS e^+p		417/379
CC cross section HERA I H1+ZEUS e^-p		20/34
CC cross section HERA I H1+ZEUS e^+p		36/34
CMS W^\pm muon charge asymmetry $\mathcal{A}(\eta_\mu)$		14/11
CMS $W + c$ cross section $\frac{d\sigma_{W+c}}{d\eta'}$		5/5

In Fig. 12, the resulting NLO parton distributions are presented at $Q_0^2 = 1.9 \text{ GeV}^2$ and $Q^2 = m_W^2$. The strange quark distribution $s(x, Q^2)$ and the ratio $R_s(x, Q^2)$ are illustrated in Fig. 13 at the same values of Q as in Fig. 12. The total uncertainty in Fig. 12 is dominated by the parametrization uncertainty in which most of the expansion in the envelope is caused by the decoupling parameter choice $B_{\bar{s}} \neq B_{\bar{d}}$. The strange-quark fraction rises with energy and reaches a value comparable to that of u and d antiquarks at intermediate to low x . Also, a suppression of R_s at large x is observed, which scales differently with the energy. This result is consistent with the prediction provided by the ATLAS Collaboration [66], where inclusive W - and Z -boson production measurements were used to determine $r_s = 0.5(s + \bar{s})/\bar{d}$. In Ref. [66], the NLO value of $r_s = 1.03$ with the experimental uncertainty $\pm 0.19_{\text{exp}}$ is quoted at $x = 0.023$ and $Q^2 = 1.9 \text{ GeV}^2$. In the framework used, the two definitions of the strange-quark fraction are very similar at the starting scale Q_0^2 and the values R_s and r_s can be directly compared.

In the free- s fit, the strangeness suppression factor is determined at $Q^2 = 20 \text{ GeV}^2$ to be $\kappa_s = 0.52_{-0.10}^{+0.12}$ (exp.) $_{-0.06}^{+0.05}$ (model) $_{-0.10}^{+0.13}$ (parametrization), which is in agreement with the value [63] obtained by the NOMAD experiment at NNLO.

The impact of the measurement of differential cross sections of $W + \text{charm}$ production on the strange-quark distribution and strangeness fraction R_s is also examined by using the Bayesian reweighting [13, 14] technique. The results qualitatively support the main conclusions of the current NLO QCD analysis. Details can be found in supplemental material.

9 Summary

The $W \rightarrow \mu\nu$ lepton charge asymmetry is measured in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ using a data sample corresponding to an integrated luminosity of 4.7 fb^{-1} collected with the CMS detector at the LHC (a sample of more than 20 million $W \rightarrow \mu\nu$ events). The asymmetry is measured in 11 bins in absolute muon pseudorapidity, $|\eta|$, for two different muon p_T thresholds, 25 and 35 GeV. Compared to the previous CMS measurement, this measurement significantly reduces both the statistical and systematic uncertainties. The total uncertainty per bin is 0.2–0.4%. The data are in good agreement with the theoretical predictions using CT10, NNPDF2.3, and HERAPDF1.5 PDF sets. The data are in poor agreement with the prediction based on the MSTW2008 PDF set, although the agreement is significantly improved when using the MSTW2008CPdeut PDF set. The experimental uncertainties are smaller than the current PDF uncertainties in the present QCD calculations. Therefore, this measurement can be used to significantly improve the determination of PDFs in future fits.

This precise measurement of the $W \rightarrow \mu\nu$ lepton charge asymmetry and the recent CMS measurement of associated $W + \text{charm}$ production are used together with the cross sections for inclusive deep inelastic scattering at HERA in an NLO QCD analysis of the proton structure. The muon charge asymmetry in W -boson production imposes strong constraints on the valence-quark distributions, while the $W + \text{charm}$ process is directly sensitive to the strange-quark distribution.

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A Additional PDF distributions

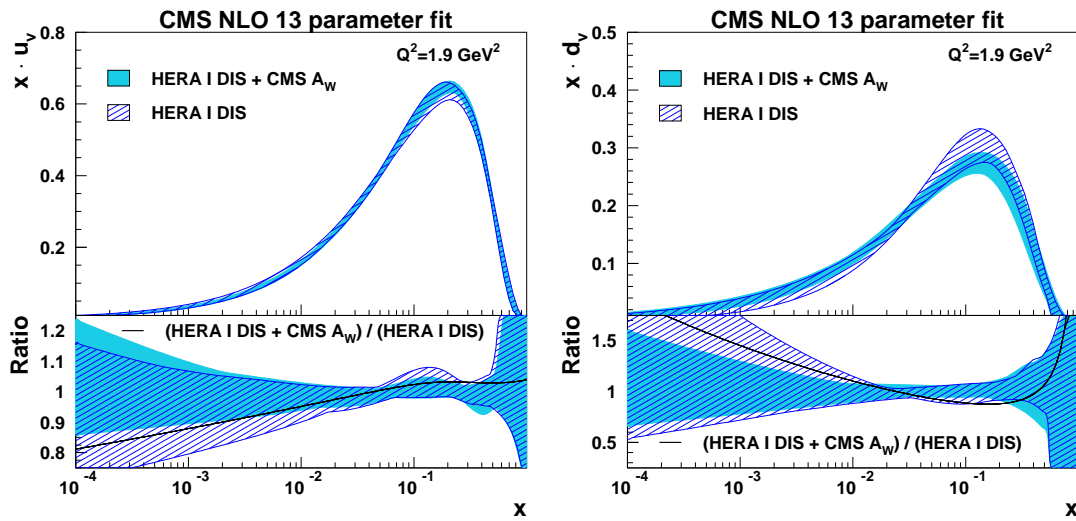


Figure 14: Distributions of u valence (left) and d valence (right) quarks as functions of x at the scale $Q^2 = 1.9 \text{ GeV}^2$. The results of the 13-parameter fixed-s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The total PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

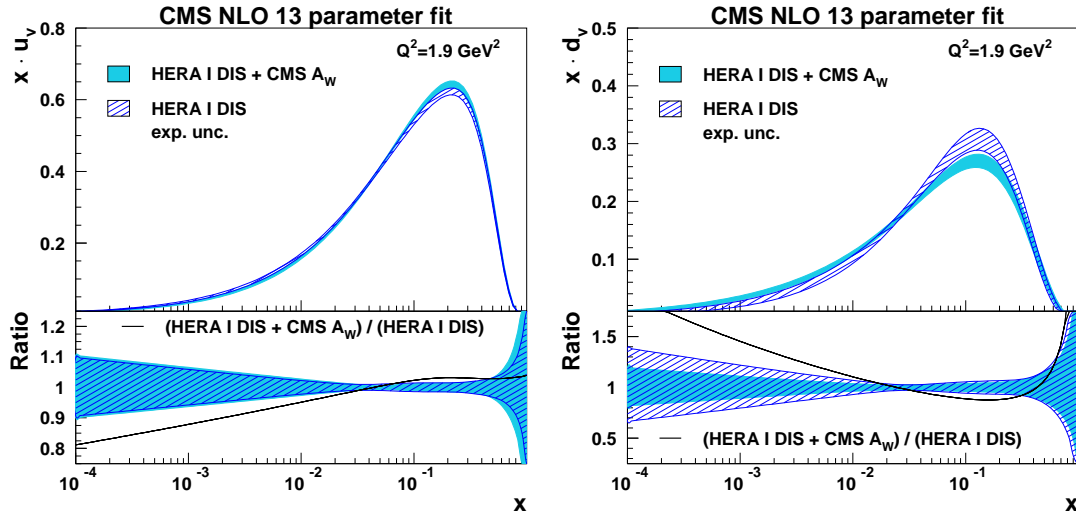


Figure 15: Distributions of u valence (left) and d valence (right) quarks as functions of x at the scale $Q^2 = 1.9 \text{ GeV}^2$. The results of the 13-parameter fixed- s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The experimental PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

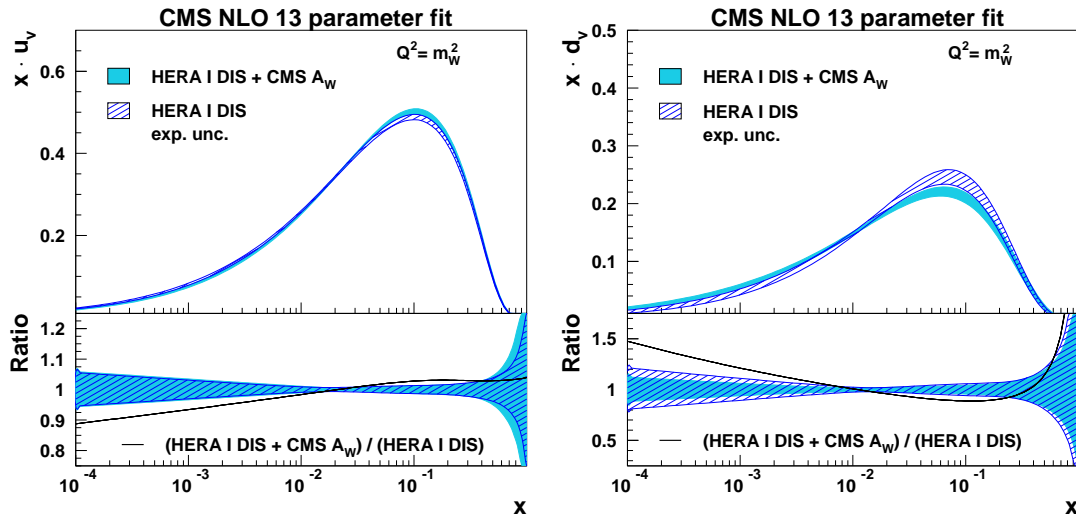


Figure 16: Distributions of u valence (left) and d valence (right) quarks as functions of x at the scale $Q^2 = m_W^2$. The results of the 13-parameter fixed- s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The experimental PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the PDFs with respect to the HERA-only fit is represented by a solid line.

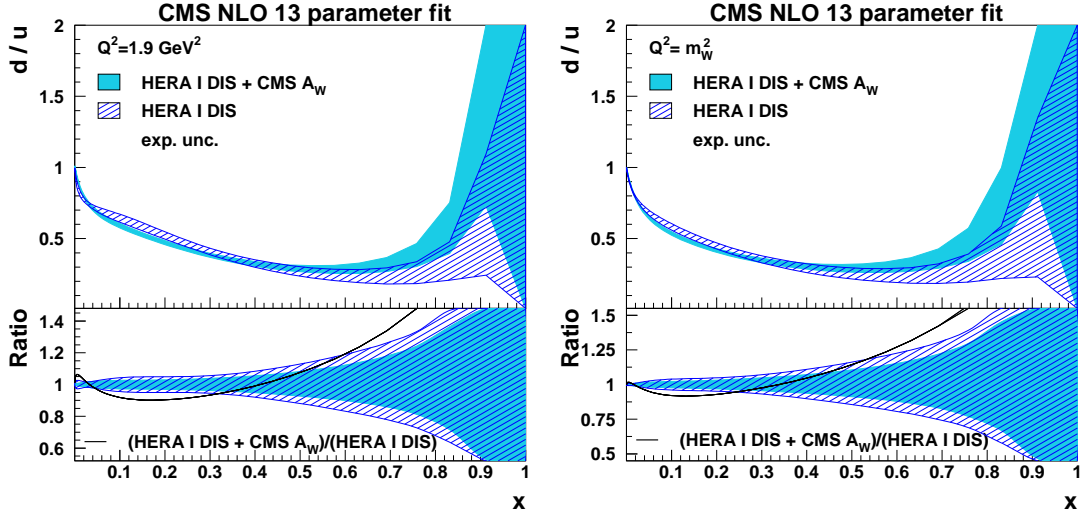


Figure 17: Ratio of d- and u-quark distributions, d/u , presented as functions of x at the scales $Q^2 = 1.9 \text{ GeV}^2$ (left) and $Q^2 = m_W^2$ (right). The results of the 13-parameter fixed-s fit to the HERA data and muon asymmetry measurements (light shaded band), and to HERA only (dark hatched band) are compared. The experimental PDF uncertainties are shown. In the bottom panels the distributions are normalized to one for a direct comparison of the uncertainties. The change of the d/u ratio with respect to the result of the HERA-only fit is represented by a solid line.

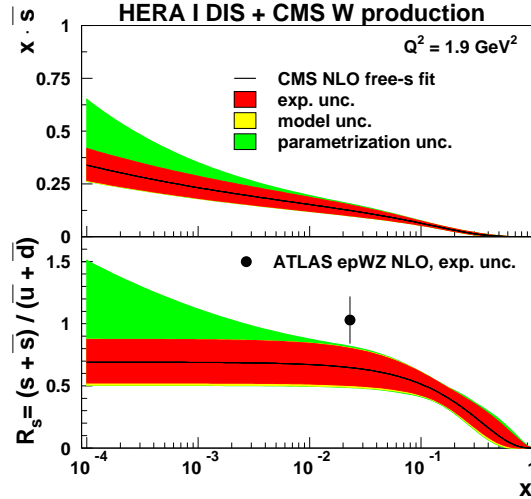


Figure 18: Antistrange-quark distribution $\bar{s}(x, Q)$ (top) and the ratio $R_s(x, Q)$ (bottom), obtained in the NLO QCD analysis of HERA and CMS data, shown as functions of x at the scale $Q^2 = 1.9 \text{ GeV}^2$. The full band represents the total uncertainty. The individual contributions from the experimental, model, and parametrization uncertainties are represented by the bands of different shades. For comparison, the NLO result of the ATLAS analysis [66] of $r_s = 0.5(s + \bar{s})/\bar{d}$ using inclusive W- and Z-boson production, is presented by a closed symbol. Only the experimental uncertainty from ATLAS is available and is shown by the vertical error bar.

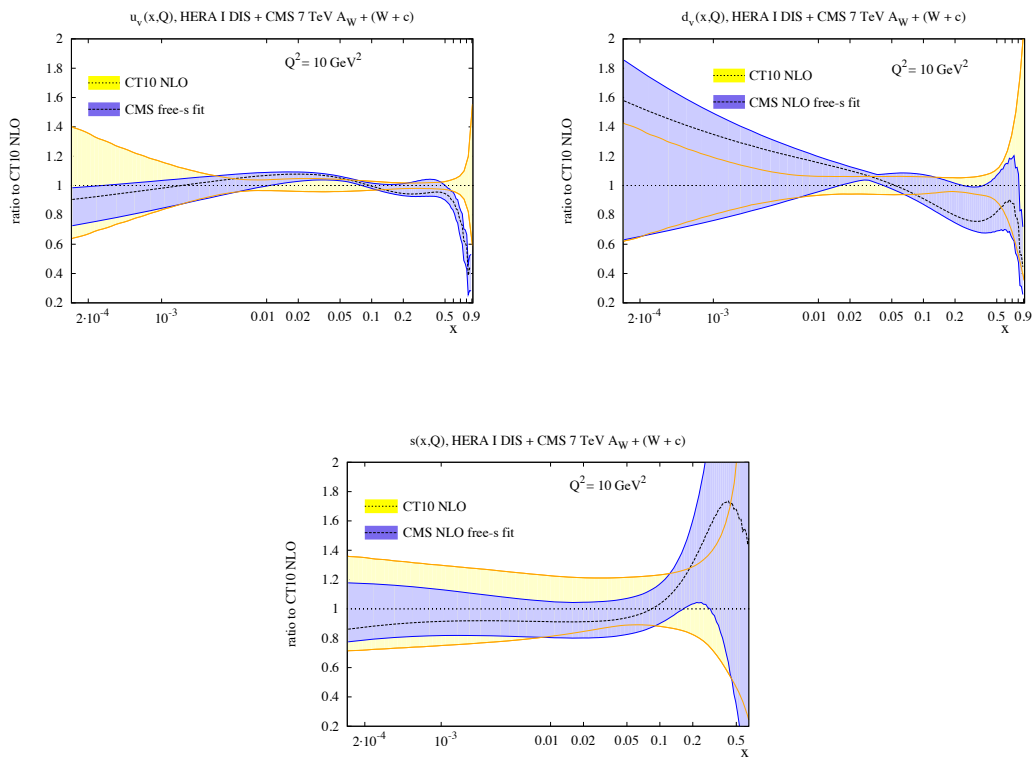


Figure 19: The distributions of u (top left), d (top right), and s (bottom) quarks, resulting from the NLO QCD analysis of HERA and CMS data, shown as functions of x at the scale $Q^2 = 10 \text{ GeV}^2$ in comparison to CT10NLO. The dark shaded band represents the total PDF uncertainty of the current fit, which is normalized to the CT10NLO central value. The light hatched band represents the CT10NLO uncertainty normalized to one. All uncertainties are given at 68% CL.

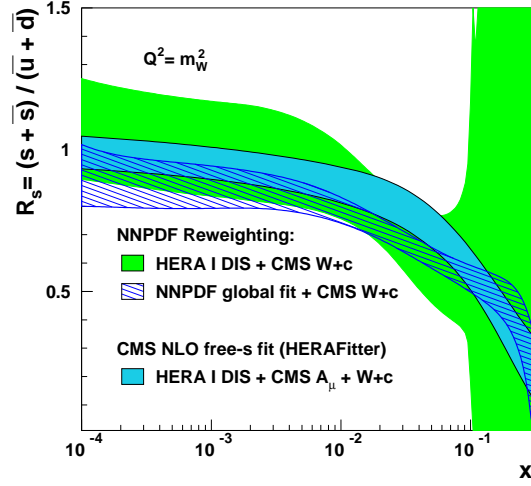


Figure 20: Ratio $R_s(x, Q^2)$ resulting from the NLO QCD analysis of HERA and CMS data, presented as a function of x at the scale $Q^2 = m_W^2$. The light shaded band represents the total PDF uncertainty of the CMS result. For comparison, results of Bayesian reweighting using HERA I inclusive DIS data and the CMS measurement of $W + \text{charm}$ production (dark shaded band). The reweighting results based on the data used in the global NNPDF2.3 fit and the CMS $W + \text{charm}$ production are represented by a hatched band.

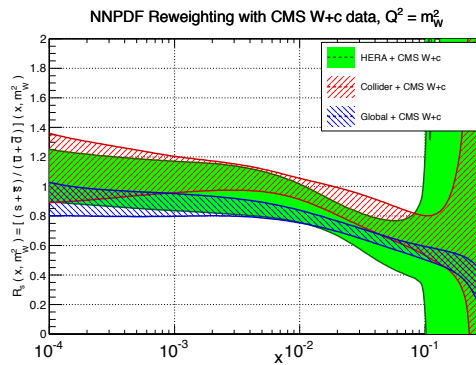


Figure 21: Ratio $R_s(x, Q^2)$, obtained by using Bayesian reweighting, shown as a function of x at the scale $Q^2 = m_W^2$. The dark shaded band represents the result based on the HERA I DIS and CMS $W + \text{charm}$ data. The results of the reweighting obtained by using the CMS $W + \text{charm}$ measurements in addition to collider-only data, and in addition to the data used in the global NNPDF2.3 analysis, are illustrated by bands of different hatches.

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