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Measurement of the electron charge asymmetry in inclusive W production in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

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Abstract

A measurement of the electron charge asymmetry in inclusive $\text{pp} \to \text{W} + X \to \text{e}\nu + X$ production at $\sqrt{s} = 7\,\text{TeV}$ is presented based on data recorded by the CMS detector at the LHC and corresponding to an integrated luminosity of $840\,\text{pb}^{-1}$. The electron charge asymmetry reflects the unequal production of W^+ and W^- bosons in pp collisions. The electron charge asymmetry is measured in bins of absolute value of electron pseudorapidity in the range of $|\eta| < 2.4$. The asymmetry rises from about 0.1 to 0.2 as a function of the pseudorapidity and is measured with a relative precision better than 7%. This measurement provides new stringent constraints for parton distribution functions.

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The dominant mechanism for W boson production in pp collisions at the Large Hadron Collider (LHC) is the annihilation of a valence quark from one proton with a sea antiquark from the other. Because the proton contains two valence u quarks and one valence d quark, W^+ bosons are produced more frequently than W^- bosons. The Compact Muon Solenoid (CMS) Collaboration measured the ratio of the inclusive W^+ and W^- production cross sections at $\sqrt{s} = 7\,\mathrm{TeV}$ at the LHC [1] to be in good agreement with the prediction of the standard model based on various parton distribution functions (PDFs) [2–7]. In this Letter we present a further investigation of inclusive W^+ and W^- production in the $W \to e\nu$ decay channel. We measure the electron charge asymmetry, defined as

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

where η is the electron pseudorapidity in the CMS lab frame ($\eta = -\ln\tan(\theta/2)$, θ is the polar angle, measured from the anticlockwise beam direction), and $\mathrm{d}\sigma/\mathrm{d}\eta$ is the differential cross section for electrons from W boson decays. Within the CMS tracker acceptance ($|\eta| < 2.5$), the asymmetry is expected to rise with increasing $|\eta|$ because the valence u quarks that produce the W^+ bosons tend to carry a higher fraction x of the proton momentum [8] than the valence d quarks that produce the W^- bosons. Measurements of the asymmetry provide constraints on the u, d, $\overline{u}$, and $\overline{d}$ PDFs in the range $10^{-3} < x < 10^{-1}$ and are complementary to measurements of deep inelastic scattering at HERA [4].

The lepton charge asymmetry and the W charge asymmetry have been studied in $p\overline{p}$ collisions by the CDF and D0 Collaborations at the Fermilab Tevatron collider [9, 10]. The ATLAS and CMS Collaborations at the LHC reported measurements of the lepton charge asymmetry in the region $|\eta| < 2.5$ using the data collected during the 2010 LHC runs [11, 12]. The LHCb Collaboration recently extended the measurement of the lepton charge asymmetry at the LHC to the $2.0 < \eta < 4.5$ region [13]. The NNPDF Collaboration estimated the impact of the CMS and ATLAS results on the PDFs [5]; the uncertainty on the light flavour and antiflavour distributions is reduced by 20% at $x \sim 10^{-3}$ and by 10–25% at larger x values.

The results presented in this Letter significantly improve the measurement of the electron charge asymmetry in inclusive $pp \to W + X \to e\nu + X$ production at $\sqrt{s} = 7\,\mathrm{TeV}$ and are based on a data sample corresponding to $840\,\mathrm{pb}^{-1}$ collected in Spring 2011. This analysis uses the portion of the 2011 dataset for which the single-electron trigger threshold was relatively low. Compared to the analysis performed in 2010 [12], the threshold on the electron transverse momentum (p_{T}) is increased from 25 to 35 GeV to match the higher trigger threshold for single electrons. The data sample is ∼25 times larger than in 2010 and allows a reduction of many systematic uncertainties.

A detailed description of the CMS experiment can be found elsewhere [14]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, 13 m in length, providing an axial field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke of the solenoid. The most relevant subdetectors for this measurement are the ECAL and the tracking system. The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in the barrel region and $1.48 < |\eta| < 3.00$ in two endcap regions. A preshower detector consisting of two planes of silicon sensors interleaved with a total of $3X_0$ of lead is located in front of the ECAL endcaps. The energy resolution measured for electrons from Z decays varies across the acceptance of the ECAL. It is less than

2% in the central region of the ECAL barrel ($|\eta| < 1$), 3% in the outer barrel, and approximately 4–5% in the endcaps.

The $W \to e\nu$ candidates are characterized by a high-p_T electron accompanied by missing transverse energy $\not\!\!E_T$, due to the escaping neutrino. Experimentally, $\not\!\!E_T$ is determined as the magnitude of the negative vector sum of the transverse momenta of all particles reconstructed using a particle-flow algorithm [15] and, in this measurement, $\not\!\!E_T$ is used to separate signal from background on a statistical basis. The $W \to e\nu$ candidates used in this analysis were collected using a set of inclusive single-electron triggers that did not include $\not\!\!E_T$ requirements. Multijet and photon+jet production (QCD backgrounds) can give rise to high-p_T electron candidates and mimic W decays. Other background sources include Drell–Yan ($Z/\gamma^* \to \ell^+\ell^-$) and $W \to \tau\nu$ production (electroweak or EW backgrounds), as well as top-quark pair ($t\bar{t}$) production.

Monte Carlo (MC) simulation samples are used to develop analysis techniques and estimate some of the background contributions. The signal and the EW backgrounds are simulated with the POWHEG [16] event generator interfaced with the CT10 [3] PDF model. The $t\bar{t}$ background is generated with the MADGRAPH [17] event generator interfaced with the CTEQ6L [18] PDF model. All generated events are passed through the CMS detector simulation using GEANT4 [19] and then processed with a reconstruction sequence identical to that used for collision data.

The selection criteria for electron identification are similar to those used in the W and Z cross section measurements [1]. A brief summary is given here for completeness. Electrons are identified as clusters of energy deposited in the ECAL fiducial volume matched to tracks from the silicon tracker. The tracks are reconstructed using a Gaussian sum filter (GSF) algorithm [20] that takes into account possible energy loss due to bremsstrahlung in the tracker layers. Particles misidentified as electrons are suppressed by requiring that the shower shape of the ECAL cluster be consistent with an electron candidate, and that the η and ϕ coordinates of the track trajectory extrapolated to the ECAL match those of the ECAL cluster. The azimuthal angle ϕ is measured in the plane perpendicular to the beam axis. Furthermore, electrons from W decay are expected to be isolated from other activity in the event. We therefore require that little transverse energy be observed in the ECAL, HCAL, and silicon tracking system within a cone $\Delta R < 0.3$ around the electron direction, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and where the calorimeter energy deposits and the track associated with the electron candidate are excluded.

A large fraction of electrons radiate photons, owing to the substantial amount of material in front of the ECAL detector. These photons may convert close to the original electron trajectory, leading to a non-negligible charge misidentification probability. Three different methods are used to determine the electron charge. First, the electron charge is determined by the signed curvature of the associated GSF track. Second, the charge is determined from the associated trajectory reconstructed in the silicon tracker using a Kalman filter algorithm [21]. Third, the electron charge is determined from the azimuthal angle between the vector joining the nominal interaction point and the ECAL cluster position and the vector joining the nominal interaction point and the innermost hit of the GSF track. It is required that all three charge determinations from these methods agree. This procedure significantly reduces the charge misidentification probability to 0.01% in the ECAL barrel and to 0.3% in the ECAL endcaps. The electron pseudorapidity is measured from the GSF track at the pp interaction point; the uncertainty on η is negligible for this analysis.

The $W \to e\nu$ candidates are selected by requiring electrons to have transverse momentum $p_T > 35\,\text{GeV}$, $|\eta| < 2.4$, and to be associated with one of the electron trigger candidates used to select the electron dataset. The Drell–Yan and $t\bar{t}$ backgrounds are suppressed by rejecting events that contain a second isolated electron or muon with $p_T > 15\,\text{GeV}$ and $|\eta| < 2.4$. According to

MC simulations, the data sample of selected electrons consists of about 16% QCD background events, about 7.4% EW background events, and about 0.4% $t\bar{t}$ background events.

As the forward and backward hemispheres are equivalent in pp collisions, the asymmetry results are presented as a function of the absolute value of the electron pseudorapidity. The selected events are divided into bins of $|\eta|$ with bin width 0.2. The region of $|\eta|$ between 1.4 and 1.6 is excluded because the cables and services in the transition region between the ECAL barrel and endcaps cause a significant reduction in the efficiency and purity of the W selection. A total of 1 229 315 $W^+ \to e^+\nu$ candidates and 991 256 $W^- \to e^-\overline{\nu}$ candidates are selected in the 11 bins of $|\eta|$.

A binned extended maximum-likelihood fit is performed to the $\not{E}_T$ distribution to estimate the $W \to e\nu$ signal yield for electrons (N^-) and positrons (N^+) in each pseudorapidity bin. The signal $\not{E}_T$ shape is derived from MC simulations with an event-by-event correction to account for differences in energy scale and resolution between data and simulation inferred from the hadronic recoil energy distributions in $Z/\gamma^* \to e^+e^-$ events selected from data [22]. The shape of the QCD background is determined, for each charge, from a signal-free control sample obtained by inverting a subset of the electron identification criteria [1]. The $\not{E}_T$ shapes for other backgrounds such as the Drell–Yan process, $t\bar{t}$, and $W \to \tau\nu$ are taken from MC simulations with a fixed normalization relative to the $W \to e\nu$ yields. The normalization factors are calculated from the predicted values of the cross sections at next-to-leading order (NLO). The yield of the QCD background and the yield of the $W \to e\nu$ signal ($N^\pm$) are free parameters in the fit. The results of the fits to the data are shown for the first ($|\eta| < 0.2$) and the tenth ($2.0 < |\eta| < 2.2$) pseudorapidity bins in Fig. 1. The uncertainty in each bin represents the systematic and statistical components associated with the $N^\pm$ extraction procedure. The ratio of the QCD background yields estimated from the fit to the $\not{E}_T$ distributions for positive and negative electrons is consistent with unity. The EW background yield for positive electrons is larger than for negative electrons because of the contribution of $W \to \tau\nu$ events. The charge asymmetry is obtained from the $(N^+ - N^-)/(N^+ + N^-)$ ratio.

Two sources of systematic uncertainty are related to the signal $\not{E}_T$ shape, the PDF used to generate the events and the uncertainty on the correction from the hadronic recoil applied to the signal $\not{E}_T$ shape. The PDF uncertainties and their effects on the measured asymmetries are evaluated using the prescription given by the PDF4LHC Working Group [23]. Uncertainties on the correction from the hadronic recoil obtained from data are also propagated to the asymmetry measurements. The systematic uncertainty due to the QCD background shape is evaluated by studying samples from different QCD background control regions. The systematic uncertainty due to the modelling of Drell–Yan, $t\bar{t}$, and $W \to \tau\nu$ is estimated by varying the relative normalization of the EW backgrounds to the $W \to e\nu$ yield by the uncertainty on the Drell–Yan and $t\bar{t}$ cross sections, and the effect on the observed asymmetry is negligible. The values of $N^\pm$ from the fitting procedure are insensitive to the presence of pile-up interactions because the $\not{E}_T$ distributions are obtained from data.

In order to compare our results directly to theoretical predictions, the observed charge asymmetry is corrected for three detector effects: 1) electron energy scale and resolution, 2) relative detection efficiency of positrons and electrons, and 3) electron charge misidentification.

The electron energy scale and resolution can bias the asymmetry because of the effect on electrons with transverse momentum close to the threshold value of 35 GeV. The electron energy scale and resolution are determined directly from the $Z/\gamma^* \to e^+e^-$ data and are used to adjust the simulated electron energy at the generator level. The correction to the measured charge asymmetry is estimated in each pseudorapidity bin by comparing the charge asymmetry as de-

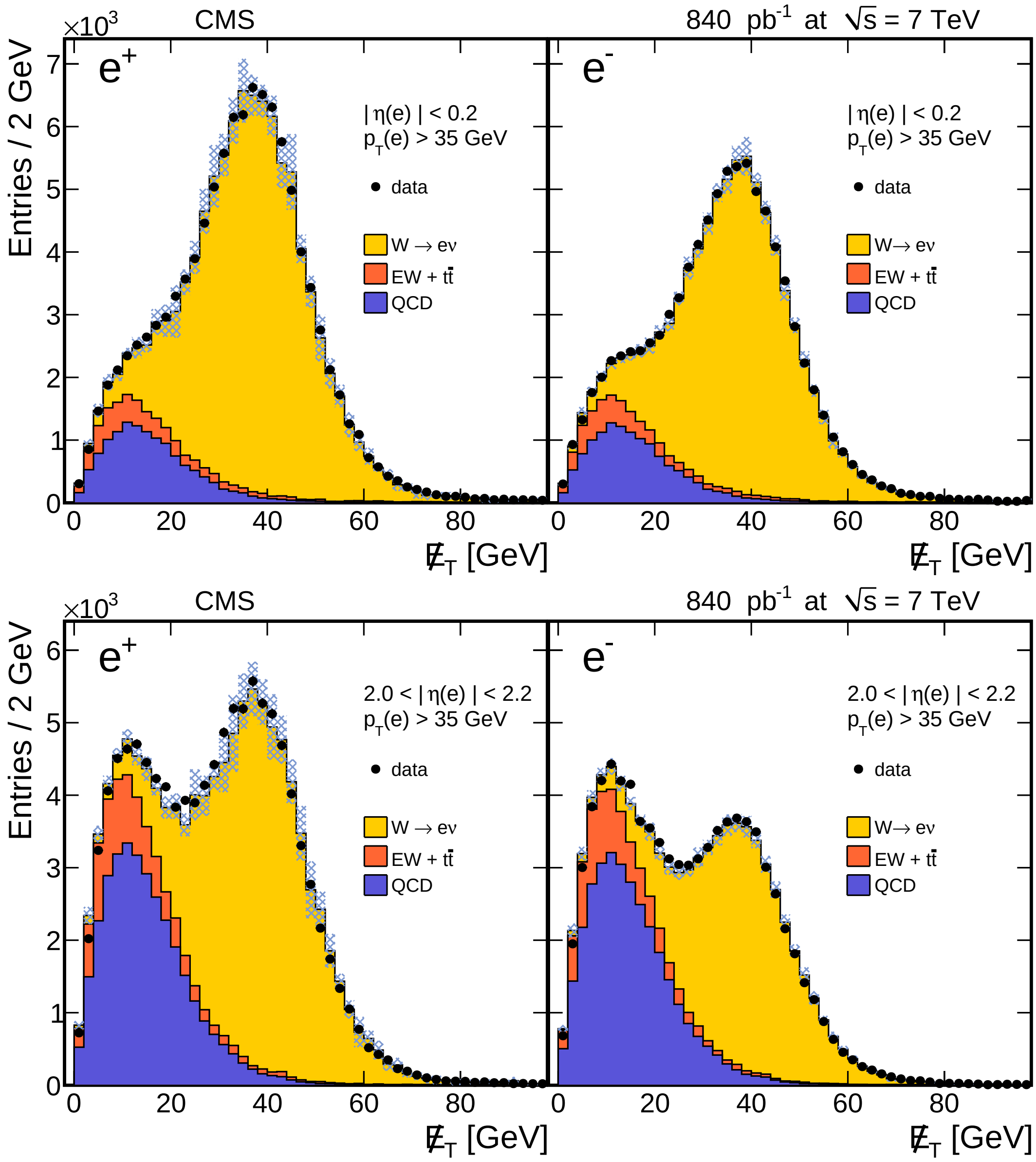

Figure 1: Signal plus background fit to data $\not\!\!E_T$ distributions for positrons (left) and electrons (right) in data. Results are shown for the first pseudorapidity bin ($|\eta| < 0.2$, top) and for the tenth pseudorapidity bin ($2.0 < |\eta| < 2.2$, bottom). The hatched area represents the statistical and systematic uncertainties associated with the fitting procedure.

termined in the simulation with the resulting asymmetry after smearing. The corrections for the electron energy scale and resolution are found to fall between -4.4×10^{-3} and 0.2×10^{-3}. The uncertainties on the energy scale and resolutions are taken as sources for systematic uncertainties. The charge asymmetry is also corrected for final-state radiation, and the uncertainty on the correction is taken as an additional systematic uncertainty, which is summed in quadrature with the uncertainty on the electron energy scale and resolution.

Any efficiency difference between electrons and positrons would bias the measured charge asymmetry. The total electron efficiency (including electron reconstruction, identification, and trigger efficiencies) in each pseudorapidity bin is measured using the $Z/\gamma^* \to e^+e^-$ data, separately for e^- and e^+, using the tag-and-probe method [1]. The efficiency ratio is calculated and found to be between 0.96 and 1.03; the statistical uncertainties on the efficiency ratios (0.01–0.03) are treated as systematic uncertainties. This is the dominant systematic uncertainty in all the pseudorapidity bins.

The true charge asymmetry $\mathcal{A}$ is diluted because of charge misidentification, resulting in an observed asymmetry $\mathcal{A}^{\rm obs} = \mathcal{A}(1-2w)$. The electron charge misidentification probability w is measured using $Z/\gamma^* \rightarrow e^+e^-$ events in data. The observed electron charge asymmetry is corrected for the charge misidentification probability as a function of $|\eta|$. The statistical uncertainty on the charge misidentification probability is taken as the systematic uncertainty.

Table 1 summarizes the systematic uncertainties in all the electron pseudorapidity bins. The full systematic covariance matrix is given in Table 2.

Table 1: Summary of the systematic uncertainties on the asymmetry. All values are given in units of 10^{-3}.

$\|\eta\|$ bin	Signal Yield	Energy Scale & Res.	Charge MisId.	Efficiency Ratio
$0.0 < \|\eta\| < 0.2$	1.8	0.6	<0.1	4.5
$0.2 < \|\eta\| < 0.4$	2.5	0.6	<0.1	4.4
$0.4 < \|\eta\| < 0.6$	2.7	0.3	<0.1	4.4
$0.6 < \|\eta\| < 0.8$	2.5	0.3	<0.1	4.4
$0.8 < \|\eta\| < 1.0$	1.9	0.6	0.1	4.4
$1.0 < \|\eta\| < 1.2$	2.4	1.0	0.1	4.9
$1.2 < \|\eta\| < 1.4$	2.6	0.8	0.1	5.4
$1.6 < \|\eta\| < 1.8$	3.1	0.8	0.1	9.2
$1.8 < \|\eta\| < 2.0$	2.0	1.6	0.2	8.7
$2.0 < \|\eta\| < 2.2$	2.0	2.6	0.3	10.0
$2.2 < \|\eta\| < 2.4$	2.9	2.4	0.3	12.5

Table 2: Covariance matrix for the systematic uncertainties on the asymmetry. All values are given in units of 10^{-6}. The matrix is symmetric.

$\|\eta\|$ 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]	[1.6, 1.8]	[1.8, 2.0]	[2.0, 2.2]	[2.2, 2.4]
[0.0, 0.2]	23.7										
[0.2, 0.4]	2.6	26.2									
[0.4, 0.6]	2.2	2.6	26.6								
[0.6, 0.8]	2.5	2.9	2.6	25.6							
[0.8, 1.0]	2.7	3.1	2.8	3.3	23.3						
[1.0, 1.2]	2.9	3.3	2.9	3.4	3.9	30.8					
[1.2, 1.4]	2.9	3.4	3.2	3.7	4.2	4.5	36.5				
[1.6, 1.8]	2.9	3.2	2.9	3.3	3.7	4.1	4.3	94.9			
[1.8, 2.0]	2.8	3.0	2.5	2.8	3.4	4.0	3.7	3.8	82.4		
[2.0, 2.2]	3.1	3.9	3.3	3.7	4.6	5.7	5.8	5.1	6.2	110.7	
[2.2, 2.4]	4.2	4.7	4.1	4.7	5.6	6.8	6.7	6.2	7.0	10.3	171.0

The measured charge asymmetry results are summarized in Table 3 with both statistical and systematic uncertainties shown. The statistical uncertainties in the various pseudorapidity bins are uncorrelated.

The experimental results are compared in Table 3 and in Fig. 2 to theoretical predictions obtained with the NLO MCFM [24] generator interfaced with CT10 [3], HERAPDF [4], NNPDF [5], and MSTW2008NLO [2] PDF models. The theoretical errors are estimated using the PDF reweighting technique [25]. The experimental data are in agreement with the predictions from CT10, NNPDF, and HERAPDF, while the predictions from MSTW are systematically lower than the observed asymmetry in the region $|\eta| < 1.4$.

Table 3: Summary of the measured charge asymmetry results. The first uncertainty is statistical and the second is systematic. The theoretical predictions are obtained using MCFM interfaced with four different PDF models. The PDF uncertainties are estimated using the PDF reweighting technique. All values are in units of 10^{-3}.

$\|\eta\|$ bin	Measured Asymmetry $\mathcal{A}$	Theoretical Predictions CT10	HERAPDF	MSTW	NNPDF
[0.0, 0.2]	$102 \pm 3 \pm 5$	109 ± 5	106^{+4}_{-8}	87^{+3}_{-5}	107 ± 5
[0.2, 0.4]	$111 \pm 3 \pm 5$	114 ± 5	110^{+4}_{-8}	89^{+3}_{-5}	110 ± 5
[0.4, 0.6]	$116 \pm 3 \pm 5$	119 ± 5	115^{+4}_{-8}	98^{+3}_{-5}	116 ± 5
[0.6, 0.8]	$123 \pm 3 \pm 5$	126 ± 5	122^{+4}_{-8}	103^{+3}_{-5}	123 ± 5
[0.8, 1.0]	$133 \pm 3 \pm 5$	138^{+5}_{-6}	132^{+4}_{-8}	115^{+4}_{-5}	134 ± 5
[1.0, 1.2]	$136 \pm 3 \pm 6$	146 ± 6	140^{+5}_{-8}	128^{+4}_{-5}	145 ± 5
[1.2, 1.4]	$156 \pm 3 \pm 6$	164^{+6}_{-7}	153^{+5}_{-7}	144 ± 5	158 ± 5
[1.6, 1.8]	$166 \pm 3 \pm 10$	195^{+8}_{-9}	181 ± 5	179 ± 5	190 ± 4
[1.8, 2.0]	$197 \pm 3 \pm 9$	207^{+8}_{-10}	196^{+4}_{-3}	200^{+6}_{-5}	206 ± 4
[2.0, 2.2]	$224 \pm 3 \pm 11$	224^{+8}_{-11}	211^{+5}_{-3}	213^{+6}_{-5}	219 ± 4
[2.2, 2.4]	$210 \pm 4 \pm 13$	241^{+8}_{-12}	225^{+9}_{-4}	231^{+6}_{-5}	231 ± 5

In summary, we have measured the electron charge asymmetry in the $W \to e\nu$ channel in a sample of proton-proton collisions at 7 TeV, corresponding to an integrated luminosity of $840\,\text{pb}^{-1}$. The measured asymmetry rises from about 0.1 to 0.2 as a function of the pseudorapidity, with an uncertainty that ranges from 0.006 in the central region to 0.014 in the ECAL endcaps. This precise measurement of the electron charge asymmetry in inclusive W production at the LHC provides stringent constraints for parton distribution functions.

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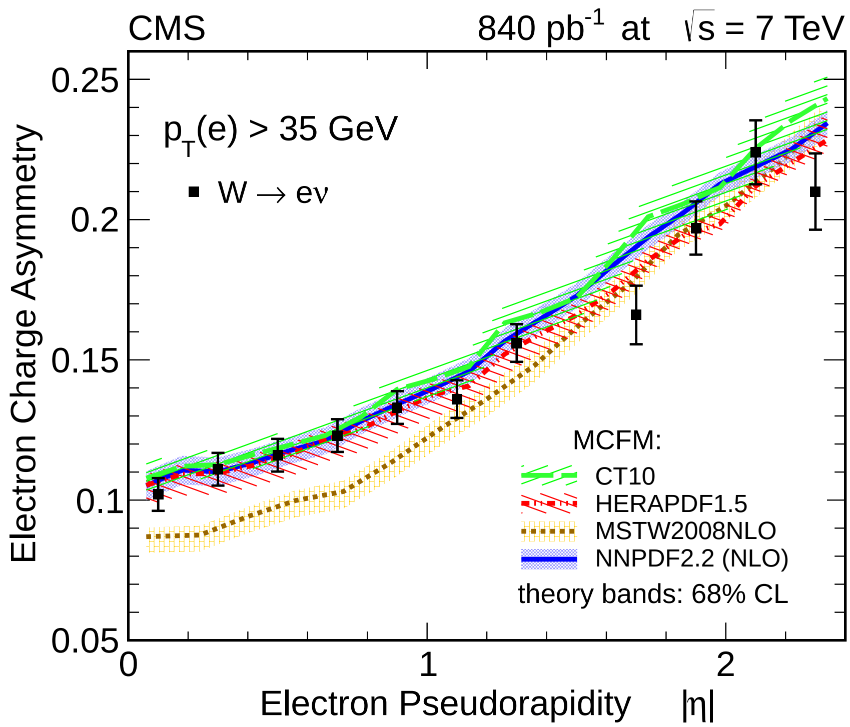

Figure 2: Comparison of the measured electron asymmetry to the predictions of different PDF models for electron $p_T > 35\,\text{GeV}$. The error bars include both statistical and systematic uncertainties. The data points are placed in the center of the $|\eta|$ bins. The PDF uncertainty bands are estimated using the PDF reweighting technique and correspond to 68% confidence level.

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