



## Journal Article

# Measurement of the lepton charge asymmetry in inclusive W production in pp collisions at root $\sqrt{s}=7$ TeV

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

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The CMS collaboration

ABSTRACT: A measurement of the lepton charge asymmetry in inclusive  $pp \rightarrow WX$  production at  $\sqrt{s} = 7$  TeV is presented based on data recorded by the CMS detector at the LHC and corresponding to an integrated luminosity of  $36 \text{ pb}^{-1}$ . This high precision measurement of the lepton charge asymmetry, performed in both the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  channels, provides new insights into parton distribution functions.

KEYWORDS: Hadron-Hadron Scattering

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**Contents**

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>The CMS detector</b>	<b>2</b>
<b>3</b>	<b>Analysis method and simulation</b>	<b>2</b>
<b>4</b>	<b>Electron reconstruction and <math>W \rightarrow e\nu</math> signal extraction</b>	<b>3</b>
<b>5</b>	<b>Muon reconstruction and <math>W \rightarrow \mu\nu</math> signal extraction</b>	<b>4</b>
<b>6</b>	<b>Systematic uncertainties</b>	<b>7</b>
<b>7</b>	<b>Results and conclusions</b>	<b>9</b>
	<b>The CMS collaboration</b>	<b>14</b>

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**1 Introduction**

In pp collisions, W bosons are produced primarily via the processes  $u\bar{d} \rightarrow W^+$  and  $d\bar{u} \rightarrow W^-$ . The first quark is a valence quark from one of the protons, and the second one is a sea antiquark from the other proton. Due to the presence of two valence u quarks in the proton, there is an overall excess of  $W^+$  over  $W^-$  bosons. The inclusive ratio of cross sections for  $W^+$  and  $W^-$  bosons production at the Large Hadron Collider (LHC) was measured to be  $1.43 \pm 0.05$  by the Compact Muon Solenoid (CMS) experiment [1] and is in agreement with predictions of the Standard Model (SM) based on various parton distribution functions (PDFs) [2, 3]. Measurement of this production asymmetry between  $W^+$  and  $W^-$  bosons as a function of boson rapidity can provide new insights on the u/d ratio and the sea antiquark densities in the ranges of the Björken parameter  $x$  [4] probed in pp collisions at  $\sqrt{s} = 7$  TeV. However, due to the presence of neutrinos in leptonic W decays the boson rapidity is not directly accessible. The experimentally accessible quantity is the lepton charge asymmetry, defined to be

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

where  $\ell$  is the daughter charged lepton,  $\eta$  is the charged lepton pseudorapidity in the CMS lab frame ( $\eta = -\ln[\tan(\frac{\theta}{2})]$  where  $\theta$  is the polar angle), and  $d\sigma/d\eta$  is the differential cross section for charged leptons from W boson decays. The lepton charge asymmetry can be used to test SM predictions with high precision. Due to the V – A structure of the W boson couplings to fermions, theoretical predictions of the charge asymmetry depend on the transverse momentum ( $p_T$ ) threshold applied on the daughter leptons. For this reason, we measure  $\mathcal{A}(\eta)$  for two different charged lepton  $p_T$  ( $p_T^\ell$ ) thresholds, 25 GeV/c and 30 GeV/c.

The lepton charge asymmetry and the W charge asymmetry have been studied in  $p\bar{p}$  collisions by both the CDF and D0 experiments at the Fermilab Tevatron Collider [5, 6]. Current predictions for the lepton charge asymmetry at the LHC based on different PDF models do not agree well with each other. A high precision measurement of this asymmetry at the LHC can contribute to the improvement of the knowledge of PDFs. The measurement of the muon charge asymmetry at the LHC with a dataset corresponding to an integrated luminosity of about  $31 \text{ pb}^{-1}$  was reported recently by the ATLAS experiment [7]. In this Letter, we present a measurement of the lepton charge asymmetry in both  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  final states using a dataset corresponding to an integrated luminosity of  $36 \text{ pb}^{-1}$  collected by the CMS detector in March-November 2010.

## 2 The CMS detector

A detailed description of the CMS experiment can be found elsewhere [8]. 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 sub-detectors for this measurement are the ECAL, the muon system, and the tracking system. The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals which provide coverage in pseudorapidity  $|\eta| < 1.479$  in the barrel region and  $1.479 < |\eta| < 3.0$  in two endcap regions. A preshower detector consisting of two planes of silicon sensors interleaved with a total of  $3 X_0$  of lead is located in front of the ECAL endcaps. The ECAL has an ultimate energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The electron energy resolution is 3% or better for the range of electron energies relevant for this analysis. Muons are measured in the pseudorapidity range  $|\eta| < 2.4$ , with detection planes made of three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution of about 2% in the relevant muon  $p_T$  range.

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

## 3 Analysis method and simulation

The  $W \rightarrow \ell\nu$  candidates are characterized by a high- $p_T$  lepton accompanied by missing transverse energy  $\cancel{E}_T$ , due to the escaping neutrino. Experimentally,  $\cancel{E}_T$  is determined as the negative vector sum of the transverse momenta of all particles reconstructed using a particle flow algorithm [9]. The  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  candidates used in this analysis were collected using a set of inclusive single-electron and single-muon triggers

which did not include  $\cancel{E}_T$  requirements. Other physics processes, such as multijet and photon+jet production (QCD background), Drell-Yan ( $Z/\gamma^* \rightarrow \ell^+\ell^-$ ) production,  $W \rightarrow \tau\nu$  production (EWK background), and top quark pair ( $t\bar{t}$ ) production can produce high- $p_T$  electron/muon candidates and mimic  $W$  candidates. Furthermore, cosmic ray muons can produce fake  $W \rightarrow \mu\nu$  candidates. The muon measurement relies on the muon detector, inner tracking and calorimeters to form a robust isolation variable to separate signal from background. This method is not applicable to the electron measurement because electron candidates are accompanied by significant electromagnetic radiation, reducing the power of the isolation in extracting signal from background. Instead the electron selection relies on the calorimeter system and uses the  $\cancel{E}_T$  to separate signal from background. These two measurements are largely independent and cross-check each other.

Monte Carlo (MC) simulation samples have been used to develop analysis techniques and estimate some of the background contributions. The next-to-leading order (NLO) MC simulations based on the POWHEG event generator [10] interfaced with the CT10 PDF model [3] are primarily used. The QCD multijet background is generated with the PYTHIA event generator [11] interfaced with the CTEQ6L PDF model [12]. The  $t\bar{t}$  background is generated using both PYTHIA and MC@NLO [13] event generators. Other PYTHIA-based MC simulations are used to cross-check MC predictions and help assigning experimental systematic uncertainties. The PYTHIA-based MC samples are normalized using NLO cross sections except for the QCD background samples. All generated events are passed through the CMS detector simulation using GEANT4 [14] and then processed using a reconstruction sequence identical to that used for collision data. Pile-up, which consists of the presence of secondary minimum bias interactions in addition to the primary hard interaction in an event, is significant in the data, where an average of 2–3 vertices are found. The analysis methods used in both electron and muon channels are insensitive to the effect of pile-up.

The selection criteria for electron/muon reconstruction and identification are almost identical to those used in the  $W$  and  $Z$  cross section measurements [1]. A brief summary is given here for completeness.

#### 4 Electron reconstruction and $W \rightarrow e\nu$ signal extraction

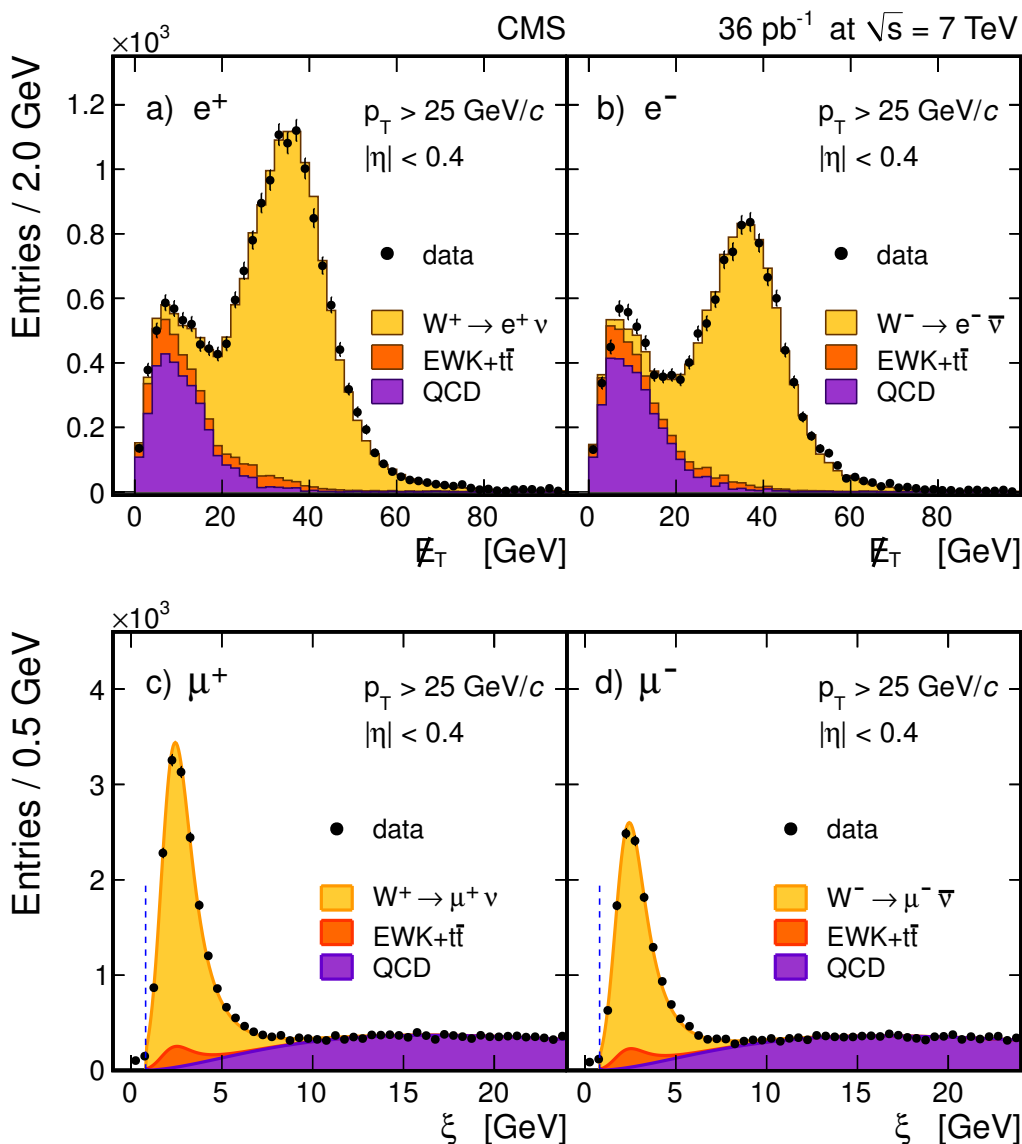
Electrons are identified as clusters of energy deposited in the ECAL fiducial volume matched to tracks from the inner silicon tracker (*silicon tracks*). The silicon tracks are reconstructed using a Gaussian-Sum-Filter (GSF) algorithm [15] that takes into account possible energy loss due to bremsstrahlung 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  $\eta$  and  $\phi$  coordinates of the track trajectory extrapolated to the ECAL match the  $\eta$  and  $\phi$  coordinates of the ECAL cluster. Furthermore, electrons from  $W$  decay are 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 calorimeter energy deposits and the track associated with the electron candidate

are excluded. Due to the substantial amount of material in front of the ECAL detector, a large fraction of electrons radiate photons. The resulting photons may convert close to the original electron trajectory, leading to a sizable charge misidentification rate ( $w$ ). The true charge asymmetry,  $\mathcal{A}^{\text{true}}$ , is diluted due to charge misidentification resulting in an observed asymmetry,  $\mathcal{A}^{\text{obs}} = \mathcal{A}^{\text{true}}(1 - 2w)$ . 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 [16]. Third, the electron charge is determined based on 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 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 rate to 0.1% in the ECAL barrel and to 0.4% in the ECAL endcaps. The  $W \rightarrow e\nu$  candidates are selected by further requiring electrons to have  $p_T > 25 \text{ GeV}/c$ ,  $|\eta| < 2.4$ , 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  $p_T > 15 \text{ GeV}/c$  and  $|\eta| < 2.4$ . According to MC simulations, the data sample of selected electrons consists of about 28% QCD background events, about 6.5% EWK background events, and about 0.2%  $t\bar{t}$  background events. The events passing the above selection criteria are divided into six bins of electron pseudorapidity ( $|\eta^e|$ ):  $[0.0, 0.4]$ ,  $[0.4, 0.8]$ ,  $[0.8, 1.2]$ ,  $[1.2, 1.4]$ ,  $[1.6, 2.0]$ , and  $[2.0, 2.4]$ , for the measurement of the electron charge asymmetry. (The fourth bin is reduced to a width of 0.2 in order to exclude the transition region between the ECAL barrel and endcaps.)

A binned extended maximum likelihood fit is performed over the  $\cancel{E}_T$  distribution to estimate the  $W \rightarrow e\nu$  signal yield for electrons ( $N^-$ ) and positrons ( $N^+$ ) in each pseudorapidity bin. The signal  $\cancel{E}_T$  shape is derived from MC simulations with an event-by-event correction to account for energy scale and resolution differences between data and MC based on the hadronic recoil energy distributions in  $Z/\gamma^* \rightarrow e^+e^-$  events selected from data [17]. 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. The  $\cancel{E}_T$  shapes for other backgrounds such as the Drell-Yan process,  $t\bar{t}$ , and  $W \rightarrow \tau\nu$  are taken from MC simulations with a fixed normalization relative to the  $W \rightarrow e\nu$  yields. The normalization factors are from the predicted values of the cross sections at NLO. The yield of the QCD background and the yield of the  $W \rightarrow e\nu$  signal are free parameters in the fit. The results of the fits to the data are shown for the first pseudorapidity bin in figures 1(a) and 1(b). The charge asymmetry is obtained from  $(N^+ - N^-)/(N^+ + N^-)$ .

## 5 Muon reconstruction and $W \rightarrow \mu\nu$ signal extraction

Muon candidates are reconstructed using two different algorithms: one starts from inner silicon tracks and requires a minimum number of matching hits in the muon chambers, and the other finds tracks in the muon system and matches them to silicon tracks. A global track fit including both the silicon track hits and muon chamber hits is performed



**Figure 1.** Signal fit to data  $\cancel{E}_T$  distributions for electrons, a)  $W^+ \rightarrow e^+\nu$ , b)  $W^- \rightarrow e^-\bar{\nu}$ , and fit to  $\xi$  distributions for muons, c)  $W^+ \rightarrow \mu^+\nu$ , and d)  $W^- \rightarrow \mu^-\bar{\nu}$ . Only the results for the first pseudorapidity bin ( $|\eta| < 0.4$ ) are shown. In figures c) and d), only events on the right of the dashed vertical line are included in the fit. The QCD (multijet and photon+jet production) shape is determined directly from data.

to improve the quality of the reconstructed muon candidates. The muon candidate is not required in this analysis to be isolated from other event activity, a difference in muon selection with respect to [1], in order to avoid bias in the signal extraction fit described below. The muon charge is identified from the signed curvature of the associated silicon track. A selection on the silicon track distance of closest approach to the beam spot,  $|d_{xy}| < 0.2$  cm, is applied to reduce the cosmic ray

background yield is estimated by normalizing the  $|d_{xy}|$  distribution derived from cosmic ray muon data to the large  $|d_{xy}|$  region ( $1.0 < |d_{xy}| < 5.0$  cm) in the data sample. The estimated cosmic ray background contamination is about  $10^{-5}$  of the expected  $W \rightarrow \mu\nu$  signal yield and is neglected. The  $W \rightarrow \mu\nu$  candidates are selected by further requiring the muon  $p_T$  to be greater than 25 GeV/c,  $|\eta| < 2.1$ , and that the candidate matches one of the muon trigger candidates. The Drell-Yan background is suppressed by rejecting events which contain a second isolated muon with  $p_T > 15$  GeV/c,  $|\eta| < 2.4$ , and passing the above muon quality selections. The events which passed the above selection criteria are divided into six bins of muon pseudorapidity ( $|\eta^\mu|$ ): [0.0, 0.4], [0.4, 0.8], [0.8, 1.2], [1.2, 1.5], [1.5, 1.8], and [1.8, 2.1].

The  $W \rightarrow \mu\nu$  signal estimation is done by fitting the distribution of an isolation variable  $\xi = \Sigma(E_T)$  defined as the scalar sum of the transverse momenta of silicon tracks (excluding the muon candidate) and energy deposits in both ECAL and HCAL in a cone  $\Delta R < 0.3$  around the muon direction. The calorimeter energy deposit associated with the muon candidate is rescaled to ensure a uniform transverse energy response as a function of polar angle. With this correction the shape of the signal  $\xi$  distribution becomes independent of pseudorapidity, peaking at a constant  $E_T$  value of about 2.5 GeV. The correction was obtained from muons in the  $Z/\gamma^* \rightarrow \mu^+\mu^-$  MC sample and checked with real muons from the  $Z/\gamma^* \rightarrow \mu^+\mu^-$  data sample. The shape of the  $\xi$  distribution for muons from  $W \rightarrow \mu\nu$  is parametrized as a Landau distribution convolved with a Gaussian resolution function. The tail of the Landau distribution is modified to be an exponential function. The  $W \rightarrow \mu\nu$  signal, the Drell-Yan background, the  $t\bar{t}$  background, and the  $W \rightarrow \tau\nu$  background have been shown in MC simulations to have  $\xi$  distributions that are identical and lepton-charge independent. The charge independence has been confirmed in studies of  $Z/\gamma^* \rightarrow \mu^+\mu^-$  data. In the final fit the shape parameters for the signal  $\xi$  distribution are fixed using  $Z/\gamma^* \rightarrow \mu^+\mu^-$  data, except for the exponential tail parameters which are fixed using  $Z/\gamma^* \rightarrow \mu^+\mu^-$  MC simulations due to limited sample of  $Z/\gamma^* \rightarrow \mu^+\mu^-$  in data. The QCD background is parametrized by an empirical function  $\xi^\alpha \cdot e^{\beta\sqrt{\xi}}$ . The QCD parametrization and the value of background parameter  $\alpha$  is determined directly from data using a QCD background control sample obtained by selecting events with large impact parameter significance and little  $\cancel{E}_T$  in the event. The background parameter  $\beta$  is allowed to float. The QCD yield is determined separately for negative and positive charges. The region used for signal estimation is chosen to be  $0 < \xi < 25$  GeV. From MC studies, the expected QCD multijet, EWK, and  $t\bar{t}$  backgrounds are about 13.0%, 6.9%, and 0.3%, respectively within the interval  $0 < \xi < 10$  GeV, in which most of  $W \rightarrow \mu\nu$  signal candidates are found.

An unbinned extended maximum likelihood fit to the  $\xi$  distribution is performed simultaneously on the  $W^+ \rightarrow \mu^+\nu$  and  $W^- \rightarrow \mu^-\bar{\nu}$  candidates to determine the total  $W \rightarrow \mu\nu$  signal yield and the charge asymmetry in each pseudorapidity bin. Background events from  $Z/\gamma^* \rightarrow \mu^+\mu^-$  are selected if one of the daughter muons is outside of the detector acceptance. This part of the  $Z/\gamma^* \rightarrow \mu^+\mu^-$  background is normalized to the observed  $Z/\gamma^* \rightarrow \mu^+\mu^-$  events in data obtained by inverting the Drell-Yan veto selection. The acceptance ratio for one versus two muons from  $Z/\gamma^* \rightarrow \mu^+\mu^-$  events is estimated with MC



simulations. There are small contributions to the  $Z/\gamma^* \rightarrow \mu^+\mu^-$  background with both muons staying within the detector coverage but one of them failing reconstruction, muon identification, or isolation requirement. This background contribution is estimated directly from data. The  $Z/\gamma^* \rightarrow \tau^+\tau^-$  background is normalized to the estimated  $Z/\gamma^* \rightarrow \mu^+\mu^-$  background with ratios determined from MC simulations. The  $W \rightarrow \tau\nu$  background is normalized to the  $W \rightarrow \mu\nu$  signal yield in the data using the ratio between  $W \rightarrow \tau\nu$  background and  $W \rightarrow \mu\nu$  signal yield determined from MC simulations. The  $t\bar{t}$  background is estimated directly from MC simulations with cross sections normalized to the predicted value at NLO. The EWK and  $t\bar{t}$  backgrounds are estimated for the  $W^+ \rightarrow \mu^+\nu$  and  $W^- \rightarrow \mu^-\bar{\nu}$  candidates separately. The results of the fits to the data are shown for the first pseudorapidity bin in figures 1(c) and 1(d). Only the region  $\xi > 0.8$  GeV is included in the fit because the small region  $\xi < 0.8$  GeV exhibits a complex shape for both signal and QCD background due to the zero-suppressed readout of the CMS calorimeters. However, events in this region are included to determine the  $W \rightarrow \mu\nu$  signal yield and charge asymmetry, as the number of QCD background events in this region is negligible, confirmed by a Monte Carlo simulation study.

## 6 Systematic uncertainties

The systematic uncertainties considered for both the electron and muon channels are mainly due to the lepton charge misidentification rate, possible efficiency differences between the  $\ell^+$  and  $\ell^-$ , lepton momentum (energy) scale and resolution, and signal estimation.

The electron charge misidentification rate is measured in data using the  $Z/\gamma^* \rightarrow e^+e^-$  data sample to be within 0.1–0.4%, increasing with electron pseudorapidity. The measured electron charge asymmetry is corrected for the charge misidentification rate. The statistical error on the electron charge misidentification rate is taken as the systematic uncertainty. The muon charge misidentification rate is studied using  $W \rightarrow \mu\nu$  MC simulations and is estimated to be at the level of  $10^{-5}$ . The muon charge misidentification rate is further studied with a cosmic ray muon data sample in which one cosmic ray muon passes through the center of the CMS detector and is reconstructed as two muon candidates with opposite charge [18]. A total of 16 422 cosmic ray muon events with at least two muon candidates are selected, and no event is found to have a same sign muon pair. This constrains the muon charge misidentification rate to be less than  $10^{-4}$ . Charge misidentification therefore has a negligible effect on the measured muon charge asymmetry.

The efficiency difference between  $\ell^+$  and  $\ell^-$  can result in a bias on the measured charge asymmetry. The total lepton efficiency (including lepton reconstruction, identification, and trigger efficiencies) in each pseudorapidity bin is measured using the  $Z/\gamma^* \rightarrow \ell^+\ell^-$  data for  $\ell^+$  and  $\ell^-$ , respectively. The efficiency ratio is calculated and found to be consistent with unity within the statistical uncertainty. No correction is made to the observed charge asymmetry. However, the statistical errors on the efficiency ratios are treated as systematic uncertainties. The inclusive electron efficiency ratio is found to be  $1.007 \pm 0.014$ , and the error on this ratio is used to determine the systematic uncertainty for the electron channel. The overall muon efficiency ratio is determined to be within 0.995 to 1.015 and the corresponding statistical error ranges from 0.008 to 0.025, depending on the pseudorapidity

bin. Within the statistical uncertainty the muon efficiency ratio is also constant across the pseudorapidity coverage. However, due to a small known charge/pseudorapidity-dependent muon momentum scale bias, the statistical uncertainty on the bin-by-bin efficiency ratio is used. This is the dominant systematic uncertainty for both the electron and muon channels.

In order to compare our results directly to theoretical predictions, the measured charge asymmetry in the electron (muon) channel is corrected for lepton energy (momentum) bias and resolution effects. The lepton scale and resolution are determined directly from the  $Z/\gamma^* \rightarrow \ell^+\ell^-$  data and are used to smear MC lepton  $p_T^\ell$  at the generator level. The correction to the measured charge asymmetry is estimated in each pseudorapidity bin by comparing the charge asymmetry as determined in the MC with the resulting asymmetry after smearing. The uncertainties on the energy (momentum) scale and resolutions are taken as sources for systematic uncertainties. The electron energy scale bias is studied using  $Z/\gamma^* \rightarrow e^+e^-$  data and determined to be within 1%. The charge-dependent muon momentum scale bias is also studied using  $Z/\gamma^* \rightarrow \mu^+\mu^-$  data sample and determined to be within 1%. This energy (momentum) scale bias dominates the systematic uncertainty due to lepton energy (momentum) scale and resolution. The impact of the QED final-state radiation (FSR) on the lepton charge asymmetry is also studied using POWHEG MC samples and a reduction of the asymmetry at the level of 0.1–0.2% is found. The charge asymmetry is corrected for the FSR effect and the full correction is taken as additional systematic uncertainty which is summed in quadrature with the lepton energy (momentum) scale systematic uncertainty.

For the electron channel, the dominant systematic uncertainty on the signal and background estimation is from the modeling of the  $\cancel{E}_T$  shape for the signal. Others, such as the uncertainties on the background cross sections and QCD background shape modeling, also contribute. The systematic uncertainty due to the QCD background shape is studied by using different QCD background control regions to derive the QCD background  $\cancel{E}_T$  shape. For the muon channel, the systematic sources for signal and background estimation are due to signal and background parametrization, uncertainty in estimating Drell-Yan and  $t\bar{t}$  background yields, and the  $W \rightarrow \tau\nu$  background to  $W \rightarrow \mu\nu$  signal ratio. The largest contribution is from the estimation of Drell-Yan background which is dominated by the limited number of Drell-Yan dimuon events and variations of the acceptance ratio for one versus two muons from  $Z/\gamma^* \rightarrow \mu^+\mu^-$  events. This acceptance ratio depends on both PDF models and the Z boson  $p_T$  spectrum. The PYTHIA and POWHEG MC samples are used to estimate the ratios, and differences between these two MC simulations (at the level of 5–10%) are treated as systematic uncertainties. The  $t\bar{t}$  background yield is varied by 18.6% to reflect the theoretical uncertainty on the  $t\bar{t}$  cross section. The ratio of the  $W \rightarrow \tau\nu$  background to the  $W \rightarrow \mu\nu$  signal and ratio of the  $Z/\gamma^* \rightarrow \tau^+\tau^-$  background to the  $Z/\gamma^* \rightarrow \mu^+\mu^-$  background are estimated using both POWHEG and PYTHIA MC simulations. The differences between these two MC simulations are taken as sources of systematic uncertainties. The robustness of the signal parametrization is studied using pseudo-experiments, whose pseudo-data are obtained by sampling fully simulated MC events according to Poisson distributions with means set to the measured signal and background yields in data. A small bias on the measured charge asymmetry at the level of 0.1–0.2% is found and taken as additional systematic uncertainty on the signal estimation.

$p_T^\ell > 25 \text{ GeV}/c$												
$ \eta $ bin	Electron Channel						Muon Channel					
	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.4]	[1.6, 2.0]	[2.0, 2.4]	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.5]	[1.5, 1.8]	[1.8, 2.1]
Charge Misident.	0.02	0.03	0.03	0.08	0.09	0.10	0	0	0	0	0	0
Eff. Ratio	0.70	0.70	0.70	0.70	0.70	0.70	0.59	0.39	0.92	0.72	0.81	1.17
$e/\mu$ Scale	0.11	0.09	0.19	0.47	0.40	0.45	0.50	0.48	0.50	0.48	0.50	0.42
Sig. & Bkg. Estim.	0.16	0.19	0.26	0.33	0.25	0.25	0.23	0.29	0.34	0.40	0.53	0.58
Total	0.73	0.73	0.77	0.90	0.85	0.87	0.80	0.68	1.10	0.95	1.08	1.37
$p_T^\ell > 30 \text{ GeV}/c$												
$ \eta $ bin	Electron Channel						Muon Channel					
	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.4]	[1.6, 2.0]	[2.0, 2.4]	[0.0, 0.4]	[0.4, 0.8]	[0.8, 1.2]	[1.2, 1.5]	[1.5, 1.8]	[1.8, 2.1]
Charge Misident.	0.02	0.02	0.03	0.07	0.08	0.10	0	0	0	0	0	0
Eff. Ratio	0.70	0.70	0.70	0.70	0.70	0.70	0.59	0.39	0.93	0.72	0.82	1.18
$e/\mu$ Scale	0.07	0.17	0.26	0.46	0.53	0.55	0.80	0.78	0.83	0.81	0.73	0.77
Sig. & Bkg. Estim.	0.16	0.19	0.26	0.33	0.25	0.25	0.20	0.20	0.27	0.35	0.51	0.56
Total	0.72	0.75	0.79	0.91	0.92	0.93	1.01	0.90	1.27	1.14	1.21	1.52

**Table 1.** Summary of the systematic uncertainties. All values are in percent.

## 7 Results and conclusions

Table 1 summarizes systematic uncertainties for both the electron and muon channels. The measured charge asymmetry results are summarized in table 2 with both statistical and systematic uncertainties shown. The measurements have been repeated with a lepton  $p_T^\ell > 30 \text{ GeV}/c$ . This requirement selects a subset of events with lepton pseudorapidity closer to the W boson rapidity and enables us to test PDF predictions in a more constrained region of phase space. The electron and muon measurements are in agreement with each other. The experimental results are compared to theoretical predictions obtained using RESBOS [19–21] and MCFM [22] generators interfaced with CT10W PDF model [3]. The RESBOS generator performs a resummation at the next-to-next-to-leading logarithmic order and gives a more realistic description of the W boson  $p_T$  spectrum than a fixed-order calculation.

Figure 2 shows a comparison of these asymmetries to predictions from the MSTW2008NLO PDF model [2] and the CT10W PDF model [3]. The central values of both predictions are obtained using the MCFM MC [22] and the PDF error bands are estimated using the PDF reweighting technique [23]. Our data suggest a flatter pseudorapidity dependence of the asymmetry than the PDF models studied.

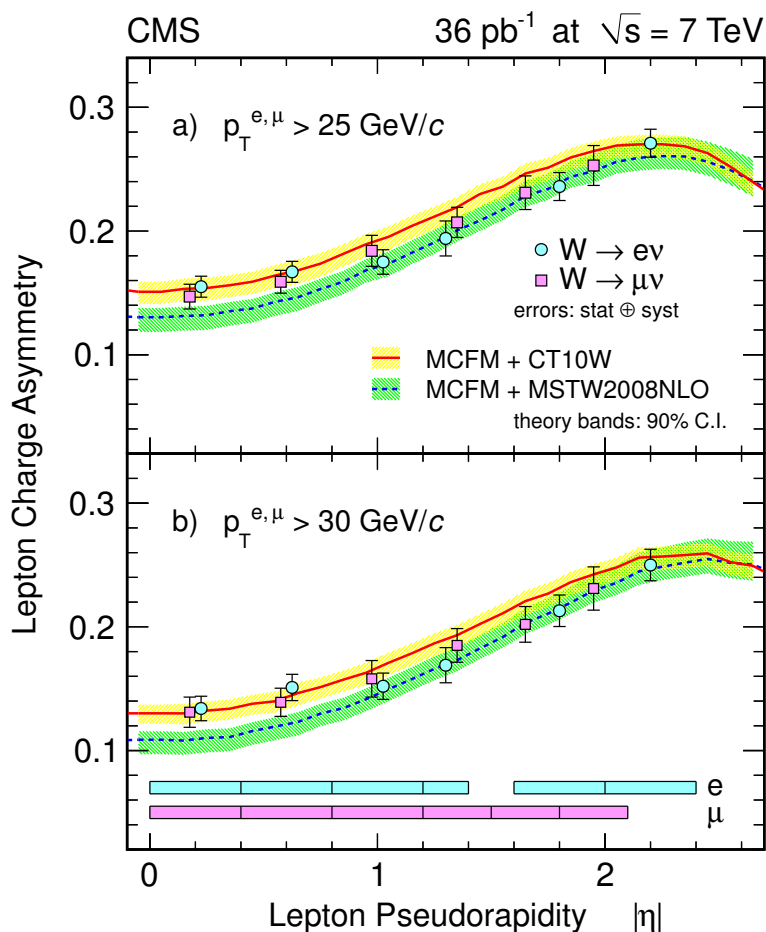
In summary, we have measured the lepton charge asymmetry in both the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  channels using a data sample corresponding to an integrated luminosity of  $36 \text{ pb}^{-1}$  collected with the CMS detector at the LHC. In each pseudorapidity bin the precision of the most inclusive measurements is less than 1.6% for both channels. This high precision measurement of the W lepton charge asymmetry at the LHC provides new inputs to the PDF global fits.

	$p_T^\ell > 25 \text{ GeV}/c$				$p_T^\ell > 30 \text{ GeV}/c$			
$ \eta^e $	$\mathcal{A}(e) (\pm\text{stat} \pm \text{sys})$	$\mathcal{A}^R$	$\mathcal{A}^M$	$\Delta(+/-)$	$\mathcal{A}(e) (\pm\text{stat} \pm \text{sys})$	$\mathcal{A}^R$	$\mathcal{A}^M$	$\Delta(+/-)$
[0.0, 0.4]	$15.5 \pm 0.6 \pm 0.7$	15.7	15.3	+0.8/-1.0	$13.4 \pm 0.7 \pm 0.7$	13.4	13.1	+0.7/-0.9
[0.4, 0.8]	$16.7 \pm 0.6 \pm 0.7$	16.9	16.7	+0.9/-1.0	$15.1 \pm 0.7 \pm 0.8$	14.6	14.5	+0.8/-0.8
[0.8, 1.2]	$17.5 \pm 0.7 \pm 0.8$	19.3	19.2	+0.8/-1.1	$15.2 \pm 0.7 \pm 0.8$	16.9	16.8	+0.8/-1.0
[1.2, 1.4]	$19.4 \pm 1.0 \pm 0.9$	21.6	21.7	+0.8/-1.1	$16.9 \pm 1.1 \pm 0.9$	19.1	18.9	+0.8/-1.0
[1.6, 2.0]	$23.6 \pm 0.8 \pm 0.9$	25.6	25.4	+0.8/-1.1	$21.3 \pm 0.9 \pm 0.9$	23.4	23.7	+0.8/-1.1
[2.0, 2.4]	$27.1 \pm 0.8 \pm 0.9$	27.1	26.9	+0.8/-1.1	$25.0 \pm 0.9 \pm 0.9$	25.7	25.4	+0.8/-1.1
$ \eta^\mu $	$\mathcal{A}(\mu) (\pm\text{stat} \pm \text{sys})$	$\mathcal{A}^R$	$\mathcal{A}^M$	$\Delta(+/-)$	$\mathcal{A}(\mu) (\pm\text{stat} \pm \text{sys})$	$\mathcal{A}^R$	$\mathcal{A}^M$	$\Delta(+/-)$
[0.0, 0.4]	$14.7 \pm 0.6 \pm 0.8$	15.7	15.3	+0.8/-1.0	$13.1 \pm 0.7 \pm 1.0$	13.4	13.1	+0.7/-0.9
[0.4, 0.8]	$15.9 \pm 0.6 \pm 0.7$	16.9	16.7	+0.9/-1.0	$13.9 \pm 0.7 \pm 0.9$	14.6	14.5	+0.8/-0.8
[0.8, 1.2]	$18.4 \pm 0.6 \pm 1.1$	19.3	19.2	+0.8/-1.1	$15.8 \pm 0.7 \pm 1.3$	16.9	16.8	+0.8/-1.0
[1.2, 1.5]	$20.7 \pm 0.7 \pm 1.0$	22.0	22.0	+0.8/-1.1	$18.5 \pm 0.8 \pm 1.1$	19.6	19.4	+0.8/-1.0
[1.5, 1.8]	$23.1 \pm 0.8 \pm 1.1$	24.6	24.5	+0.8/-1.1	$20.2 \pm 0.8 \pm 1.2$	22.2	21.9	+0.8/-1.1
[1.8, 2.1]	$25.3 \pm 0.8 \pm 1.4$	26.5	26.3	+0.8/-1.0	$23.1 \pm 0.9 \pm 1.5$	24.5	24.1	+0.8/-1.1

**Table 2.** Summary of charge asymmetry ( $\mathcal{A}$ ) results. The first uncertainty is statistical and the second is systematic. The theoretical predictions are obtained using RESBOS ( $\mathcal{A}^R$ ) and MCFM ( $\mathcal{A}^M$ ) interfaced with CT10W PDF model. The PDF uncertainties ( $\Delta(+/-)$ ) are estimated using the PDF reweighting technique. The charge asymmetries and PDF errors are given in percent. For each pseudorapidity bin the theoretical prediction is calculated using the averaged differential cross sections for positively and negatively charged leptons respectively. The statistical uncertainty on the theoretical prediction is about 0.1%.

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**Figure 2.** Comparison of the measured lepton charge asymmetry to different PDF models for a) lepton  $p_T^l > 25$  GeV/c and b) lepton  $p_T^l > 30$  GeV/c. The error bars include both statistical and systematic uncertainties. The PDF uncertainty band is corresponding to the 90% confidence interval (C.I.). The bin width for each data point is shown by the filled bars in figure b). The data points are placed at the centers of pseudorapidity bins, except that for display purposes the first three data points are shifted +0.025 (−0.025) for electron (muon).

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