Erratum: Measurement of the $W$ boson production charge asymmetry in $pp \to W + X \to e\nu + X$ events at $\sqrt{s} = 1.96$ TeV


1LAFEX, Centro Brasileiro dePesquisas Físicas, Rio de Janeiro, Brazil
2Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
3Universidade Federal do ABC, Santo André, Brazil
4University of Science and Technology of China, Hefei, People’s Republic of China
5Universidad de los Andes, Bogotá, Colombia
6Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
7Czech Technical University in Prague, Prague, Czech Republic
8Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
9Universidad San Francisco de Quito, Quito, Ecuador
10LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
11LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
12CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
13LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
14LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
15CEA, Ifuy, SPP, Saclay, France
16IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
17IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
18II. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
19Physikalisches Institut, Universität Freiburg, Freiburg, Germany
20Ludwig-Maximilians-Universität München, München, Germany
21Institut für Physik, Universität Mainz, Mainz, Germany
22Panjab University, Chandigarh, India
23Delhi University, Delhi, India
24Tata Institute of Fundamental Research, Mumbai, India
25University College Dublin, Dublin, Ireland
26Korea Detector Laboratory, Korea University, Seoul, Korea
27CINVESTAV, Mexico City, Mexico
28Nikhef, Science Park, Amsterdam, the Netherlands
29Radboud University Nijmegen, Nijmegen, the Netherlands
30Joint Institute for Nuclear Research, Dubna, Russia
31Institute for Theoretical and Experimental Physics, Moscow, Russia
32Moscow State University, Moscow, Russia
33Petersburg Nuclear Physics Institute, St. Petersburg, Russia
34Institut de Càtedra de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain
35Uppsala University, Uppsala, Sweden
36Lancaster University, Lancaster LA1 4YB, United Kingdom
37Imperial College London, London SW7 2AZ, United Kingdom
38The University of Manchester, Manchester M13 9PL, United Kingdom
39University of Arizona, Tucson, Arizona 85721, USA
40University of California Riverside, Riverside, California 92521, USA
41Florida State University, Tallahassee, Florida 32306, USA
42Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
43University of Illinois at Chicago, Chicago, Illinois 60607, USA
44Northern Illinois University, DeKalb, Illinois 60115, USA
45Northwestern University, Evanston, Illinois 60208, USA
46Indiana University, Bloomington, Indiana 47405, USA
47Purdue University Calumet, Hammond, Indiana 46323, USA
48University of Notre Dame, Notre Dame, Indiana 46556, USA
49Iowa State University, Ames, Iowa 50011, USA
50University of Kansas, Lawrence, Kansas 66045, USA
51Louisiana Tech University, Ruston, Louisiana 71272, USA
52Northern Kentucky University, Cincinnati, Ohio 45221, USA
53University of Iowa, Iowa City, Iowa 52242, USA
54University of Kansas, Lawrence, Kansas 66045, USA
55University of Michigan, Ann Arbor, Michigan 48109, USA
56Michigan State University, East Lansing, Michigan 48824, USA
The measurement of the $W$ boson production charge asymmetry published in our recent Letter \cite{1} employed a correction $K_{\pm \text{eff}}$ to take into account the relative efficiency difference between electrons and positrons. Based on a recent study \cite{2}, we realized that the determination of $K_{\pm \text{eff}}$ was incorrect. Instead of taking the ratio of the positron to electron efficiencies, we took the ratio of the numbers of reconstructed positrons to electrons. In addition, we had not taken into account the solenoid polarity when determining $K_{\pm \text{eff}}$. These two problems have now been corrected.

The corrected $W$ boson charge asymmetry values measured using the updated efficiency correction \cite{2} are given in Table \ref{tab:asymmetry}. These revised measurements, together with those from the CDF Collaboration \cite{12} are shown in Fig. \ref{fig:asymmetry}. The asymmetry values have changed relative to those in the original publication by $< 2\%$, with smaller asymmetry values for $|y_W| < 0.6$ and larger asymmetry values for $0.8 < |y_W| < 2.4$, compared to the published result \cite{1}.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
$|y_W|$ & DØ, 1 fb\textsuperscript{-1} & CDF A, 1 fb\textsuperscript{-1} \\
\hline
0 & 0.2 & 0.2 \\
0.5 & 0.1 & 0.1 \\
1 & 0.05 & 0.05 \\
1.5 & 0 & 0 \\
2 & 0 & 0 \\
2.5 & 0 & 0 \\
3 & 0 & 0 \\
\hline
\end{tabular}
\caption{Table I. Measured $W$ boson charge asymmetry, after CP-folding, compared to predictions and the CDF 1 fb$^{-1}$ result. The points show the measured asymmetry, with the horizontal bars delineating the statistical uncertainty component and the vertical lines showing the total uncertainty. The central value and uncertainty from MC@NLO using the NNPDF2.3 PDF sets and the predictions from Resbos using the CTEQ6.6 central PDF set are also shown. The inset focuses on the $y_W$ region from 0 to 1.5.}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{asymmetry}
\caption{(color online). Measured $W$ boson charge asymmetry, after CP-folding, compared to predictions and the CDF 1 fb$^{-1}$ result. The points show the measured asymmetry, with the horizontal bars delineating the statistical uncertainty component and the vertical lines showing the total uncertainty. The central value and uncertainty from MC@NLO using the NNPDF2.3 PDF sets and the predictions from Resbos using the CTEQ6.6 central PDF set are also shown. The inset focuses on the $y_W$ region from 0 to 1.5.}
\end{figure}

* with visitors from \textsuperscript{a}Augustana College, Sioux Falls, SD, USA, \textsuperscript{b}The University of Liverpool, Liverpool, UK, \textsuperscript{c}DESY, Hamburg, Germany, \textsuperscript{d}Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mexico \textsuperscript{e}SLAC, Menlo Park, CA, USA, \textsuperscript{f}University College London, London, UK, \textsuperscript{g}Centro de Investigacion en Computacion - IPN, Mexico City, Mexico, \textsuperscript{h}Universidade Estadual Paulista, Sao Paulo, Brazil, \textsuperscript{i}Karlsruher Institut für Technologie (KIT) - Steinbuch Centre for Computing (SCC), D-76128 Karlsruhe, Germany, \textsuperscript{j}Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA and \textsuperscript{k}American Association for the Advancement of Science, Washington, D.C. 20005, USA.

\begin{thebibliography}{99}
TABLE I: CP-folded $W$ boson charge asymmetry for data and predictions from MC@NLO using the NNPDF2.3 PDFs tabulated in percent (%) for each $|y_W|$ bin. The $\langle|y_W|\rangle$ is calculated as the cross section weighted average of $y_W$ in each bin from RESBOS with PHOTOS $[5]$. For data, the first uncertainty is statistical and the second is systematic. The uncertainties on the prediction come from both the PDF uncertainties and $\alpha_s$ uncertainties.

| Bin index | $|y_W|$ | $\langle|y_W|\rangle$ | Data | Prediction |
|-----------|--------|----------------|------|------------|
| 1         | 0.0–0.2| 0.10           | $1.39 \pm 0.17 \pm 0.12$ | $1.61 \pm 0.19$ |
| 2         | 0.2–0.4| 0.30           | $4.28 \pm 0.18 \pm 0.19$ | $5.06 \pm 0.33$ |
| 3         | 0.4–0.6| 0.50           | $7.28 \pm 0.19 \pm 0.27$ | $8.50 \pm 0.41$ |
| 4         | 0.6–0.8| 0.70           | $10.59 \pm 0.20 \pm 0.30$ | $12.05 \pm 0.53$ |
| 5         | 0.8–1.0| 0.90           | $14.45 \pm 0.21 \pm 0.32$ | $15.36 \pm 0.66$ |
| 6         | 1.0–1.2| 1.10           | $18.63 \pm 0.22 \pm 0.39$ | $18.86 \pm 0.74$ |
| 7         | 1.2–1.4| 1.30           | $22.50 \pm 0.24 \pm 0.44$ | $22.52 \pm 0.80$ |
| 8         | 1.4–1.6| 1.50           | $26.12 \pm 0.27 \pm 0.42$ | $26.30 \pm 0.85$ |
| 9         | 1.6–1.8| 1.70           | $30.06 \pm 0.31 \pm 0.44$ | $29.89 \pm 0.92$ |
| 10        | 1.8–2.0| 1.90           | $34.73 \pm 0.35 \pm 0.49$ | $34.04 \pm 1.08$ |
| 11        | 2.0–2.2| 2.10           | $40.59 \pm 0.40 \pm 0.54$ | $39.77 \pm 1.31$ |
| 12        | 2.2–2.4| 2.29           | $47.65 \pm 0.44 \pm 0.56$ | $47.73 \pm 1.62$ |
| 13        | 2.4–2.7| 2.52           | $59.04 \pm 0.46 \pm 0.60$ | $61.81 \pm 1.74$ |
| 14        | 2.7–3.2| 2.81           | $77.24 \pm 0.93 \pm 0.66$ | $78.05 \pm 4.36$ |

We present a measurement of the W boson production charge asymmetry in $p\bar{p} \rightarrow W + X \rightarrow e\nu + X$ events at a center of mass energy of 1.96 TeV, using 9.7 fb$^{-1}$ of integrated luminosity collected with the D0 detector at the Fermilab Tevatron Collider. The neutrino longitudinal momentum is determined by using a neutrino weighting method, and the asymmetry is measured as a function of the W boson rapidity. The measurement extends over wider electron pseudorapidity region than previous results and is the most precise to date, allowing for precise determination of proton parton distribution functions in global fits.

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At the Fermilab Tevatron Collider, production of $W^\pm$ bosons is dominated by the annihilation of valence quarks in the proton $(u, d)$ and antiquark $(\bar{d}, \bar{u})$. The primary modes of production are $u + \bar{d} \rightarrow W^+ + \bar{u} + d \rightarrow W^-$. In the proton and antiproton, the $u$ ($\bar{u}$) quark generally carries more momentum than the $\bar{d}$ ($d$) quark; thus, $W^+$ bosons are boosted in the proton direction and $W^-$ bosons in the antiproton direction. The difference between $u$ and $d$ quark parton distribution functions (PDFs) results in a charge asymmetry in the $W$ boson rapidity ($y_W$), defined as

$$A(y_W) = \frac{d\sigma_{W^+}/dy_W - d\sigma_{W^-}/dy_W}{d\sigma_{W^+}/dy_W + d\sigma_{W^-}/dy_W}$$  \hspace{1cm} (1)$$

where $d\sigma_{W^\pm}/dy_W$ is the differential cross section for $W^\pm$ boson production, and $y_W$ is the $W^\pm$ boson rapidity, defined as

$$y_W = \frac{1}{2} \ln \frac{E + p_z}{E - p_z},$$  \hspace{1cm} (2)$$

where $E$ and $p_z$ are the energy and the longitudinal momentum, respectively, of the $W$ boson, with the $z$ axis along the proton beam direction.

Previously published results include both lepton (from the $W$ boson decay) and $W$ boson charge asymmetries. The lepton charge asymmetry arises from the convolution of the $W$ boson asymmetry and the $V-A$ structure of the $W$ boson decay. This implies that leptons at a specific rapidity originate from a wide range of $W$ rapidities, and therefore from a wide range of parton $x$ values (where $x$ is the fraction of momentum of the proton carried by the parton), diluting the impact of these asymmetries when determining PDFs. The lepton charge asymmetry in $W$ boson decays has been measured by the CDF \cite{4,5} and D0 \cite{6,7} Collaborations. The latest lepton charge asymmetry measurement from the D0 Collaboration was performed in the $W \rightarrow \mu\nu$ muon channel by using data corresponding to 7.3 fb$^{-1}$ of integrated luminosity \cite{9}. The lepton charge asymmetry has also been measured at the Large Hadron Collider (LHC) in $pp$ collisions by the ATLAS \cite{10} and CMS \cite{11} Collaborations by using integrated luminosities of 0.03 and 0.84 fb$^{-1}$, respectively. A direct measurement of the $W$ boson charge asymmetry was performed by using 1 fb$^{-1}$ of integrated luminosity by the CDF Collaboration \cite{12}.

The analysis presented in this Letter uses the $W \rightarrow e\nu$ decay mode and employs the neutrino weighting method \cite{13}. In addition, this $W$ boson charge asymmetry analysis uses 10 times more integrated luminosity and covers much larger rapidity range than the previous CDF result \cite{12}. We use data corresponding to 9.7 fb$^{-1}$ of integrated luminosity \cite{14} collected with the D0 detector \cite{15,16} between April 2002 and September 2011. By extending the pseudorapidity coverage, we can provide information about the PDFs for a broader range of $x (0.002 < x < 0.99$ for electron pseudorapidity $|\eta| < 3.2$ \cite{17}) at $Q^2 \approx M_W^2$, where $Q^2$ is the squared momentum scale for the parton interactions and $M_W$ is the $W$ boson mass. The $W$ boson charge asymmetry result places stringent constraints on the PDFs of valence quarks, which in turn will significantly reduce the uncertainty on the measurements of $M_W$ and on other measurements at the Tevatron and LHC.

The D0 detector \cite{15,16} comprises a central tracking system, a calorimeter, and a muon system. The central tracking system consists of a silicon microstrip tracker and a scintillating fiber tracker (CFT). The CFT provides coverage for charged particles at detector pseudorapidities of $|\eta_{det}| < 1.7$. Three liquid argon and uranium calorimeters provide coverage of $|\eta_{det}| < 3.5$ for electrons: the central calorimeter (CC) up to $|\eta_{det}| < 1.1$ and two end calorimeters (EC) in the range $1.5 < |\eta_{det}| < 3.5$. Gaps between the cryostats create an inefficient electron detection region between $1.1 < |\eta_{det}| < 1.5$ that is excluded from the analysis. Each calorimeter consists of an inner electromagnetic (EM) section, followed by hadronic sections.

Events used in this analysis were collected with a set of calorimeter-based single-electron triggers. To select $W \rightarrow e\nu$ events, we require one EM shower with transverse energy will respect to the beam $25 < E_T < 100$ GeV measured in the calorimeter, accompanied by large missing transverse energy of $E_T > 25$ GeV. $E_T$ is estimated by the vector sum of the transverse components of the energy deposited in the calorimeter ($E_T$) and the electron $E_T$. An isolation requirement is imposed on the electron candidate, which is also required to have a significant fraction of its energy deposited in the EM calorimeter, compared to that deposited in the hadron calorimeter. Candidates in the CC must be in the range $|\eta_{det}| < 1.1$, and those in the EC must be within $1.5 < |\eta_{det}| < 3.2$, to allow a precise measurement of ele-
tron energy. The shower shape \[18\] must be consistent with that expected for an electron, and the candidate is required to be spatially matched to a reconstructed track. Because the CFT detector does not cover the entire \(y_{\text{det}}\) region used in the analysis, electron selection criteria are separately defined in four categories: CC electrons with full CFT coverage, EC electrons with full CFT coverage, EC electrons with partial CFT coverage, and EC electrons without CFT coverage. Events are further required to have the reconstructed \(p_{\text{T}}^{\text{jet}}\) interaction vertex located within 40 cm of the detector center along the z axis, a reconstructed \(W\) boson transverse mass \(M_T\) between 50 and 130 GeV, where \(M_T = \sqrt{2E_T' E_T(1 - \cos \Delta \phi)}\), and \(\Delta \phi\) is the azimuthal angle between the electron and \(E_T\), \(u_T\) less than 60 GeV, and \(SET\) less than 250 or 500 GeV depending on the data collection period, where \(SET\) is the scalar sum of all transverse energies measured by the calorimeter except those energies associated with electrons or with potential noise, reflecting the total activity in the event.

After applying the selection criteria described above, we retain 6 083 198 \(W\) boson candidates. Of these, 4 466 735 are events with the electron in the CC region and 1 616 463 with the electron in the EC region. We have checked that the asymmetry results for \(y_W > 0\) are consistent with those for \(y_W < 0\), so we assume CP invariance—i.e., \(A(y_W)\) is equivalent to \(-A(-y_W)\)—and fold the data appropriately to increase the statistics in each \(y_W\) bin. The forward-backward charge asymmetries are measured in 14 bins of \(y_W\) in the range \(|y_W| < 3.2\). The bin widths are chosen by considering the sample size and the detector geometry to ensure that high \(|y_W|\) bins retain sufficient statistics.

Mismeasurement of the charge sign of the electron may result in a dilution of the \(W\) boson charge asymmetry. We measure the charge misidentification rate with \(Z \to ee\) events, using a “tag-and-probe” method \[19\]. The tag electron must satisfy tight selection criteria to ensure its charge is determined correctly. The charge misidentification rate varies from \((0.18 \pm 0.01)\%\) at \(|\eta^e| = 0\) to \((9.6 \pm 0.9)\%\) at \(|\eta^e| = 3.0\), where \(\eta^e\) is the charge of the electron. The forward-backward charge asymmetries are measured in 14 bins of \(y_W\) in the range \(|y_W| < 3.2\). The bin widths are chosen by considering the sample size and the detector geometry to ensure that high \(|y_W|\) bins retain sufficient statistics.

Monte Carlo (MC) samples for the \(W \to ee\) process are generated by using the PYTHIA \[20\] event generator with CTEQ6L1 PDFs \[21\], followed by a GEANT-based simulation \[22\] of the D0 detector. This simulation is then corrected for higher-order effects not included in PYTHIA. The MC events are reweighted at the generator level in two dimensions (\(W\) boson transverse momentum, \(p_{T}^W\), and \(y_W\)) to match RESBOS \[23\] predictions. To improve the accuracy of the MC detector simulation, further corrections are applied to the MC simulations including electron energy scale and resolution, recoil system scale and resolution, selection efficiencies, trigger efficiencies, instantaneous luminosity and \(SET\), charge misidentification, and relative efficiency for identification of positrons and electrons \((K_{\text{el}}^+\)). These corrections are derived by comparing the \(Z \to ee\) data and PYTHIA MC distributions. Because of imperfections in the modeling of the tracking detector, differences between the efficiency for electrons and positrons vary from 0.0% at \(|\eta^e| = 0\) to 1% at \(|\eta^e| = 3.0\).

The dominant source of background originates from multijet events, with one jet misreconstructed as an electron and with significant \(E_T\) due to the mismeasurement of the jet energy. Smaller background contributions arise from other standard model (SM) processes and are estimated by using PYTHIA MC samples normalized to the highest order available cross sections \[24\]. These include \(W \to \tau \nu\) events where the tau decays to an electron and neutrinos, \(Z \to ee\) events where one of the electrons is not identified, and \(Z \to \tau \tau\) events with one tau decaying to an electron and the other not identified. The multijet background is estimated by using collider data by fitting the \(M_T\) distribution in the region 50-130 GeV (after other SM backgrounds have been subtracted) to the sum of the shape predicted by the \(W \to e\nu\) signal MC sample and the shape obtained from a multijet-enriched data sample. The multijet-enriched sample is selected by reversing the shower shape requirement on the electron candidates. The background contributions are determined as a function of \(y_W\), and average contributions are 4.0% multijet events, 2.6% \(Z \to ee\), 2.2% \(W \to \tau \nu\), and 0.2% \(Z \to \tau \tau\).

In the determination of the longitudinal momentum of the neutrino \((p_{\nu}^z)\) \[13\], \(M_W\) is fixed to the world average value of 80.385 GeV \[25\]. The mass-energy relation constraint using the energy and momentum of the neutrino and electron,

\[
M_W^2 = (E_e + E_{\nu})^2 - (\vec{P}_e + \vec{P}_\nu)^2,
\]

implies that there are two solutions in \(p_{\nu}^z\). The twofold ambiguity can be partly resolved on a statistical basis from the known \(V - A\) decay distribution by using the decay angle between the electron and the proton \((\theta^e)\) and from the \(W^+ \to W^-\) production cross sections as a function of \(y_W\). As expected, many off-shell \(W\) boson decays do not satisfy the \(M_W^2\) constraint. In this case, we obtain complex values for the \(p_{\nu}^z\), assume that the neutrino transverse momentum \((p_{\nu}^T)\) is misreconstructed, and therefore scale \(E_T\) to the value for which the imaginary part equals zero. This new \(E_T\) value is then used to determine \(p_{\nu}^T\) and therefore \(y_W\). To obtain the \(W\) boson
rapidity distributions, we assign different probabilities to the two $p_T^\pm$ solutions. This probability is related to the quark and antiquark $W^\pm$ boson production by

$$\begin{aligned}
P_{\pm}(\cos\theta^*, y_W, p_T^{W}) &= (1 - \cos\theta^*)^2 + \\
Q(y_W, p_T^{W}) &= (1 + \cos\theta^*)^2,
\end{aligned}$$

where $P_{\pm}(\cos\theta^*, y_W, p_T^{W})$ is the probability for $W$ boson production with a particular $\cos\theta^*$, $y_W$, and $p_T^{W}$. The first term in Eq. (4) represents the contribution from annihilation with two quarks, and the second term the contribution from annihilation with at least one antiquark. The ratio $Q(y_W, p_T^{W})$ between quark and antiquark $W$ boson production is a function of $W$ boson rapidity and transverse momentum. At the Tevatron, the $W$ boson production contribution from the antiquark and gluons is $\sim 10\%$.

Understanding the antiquark contribution is important for the asymmetry measurement, because $W$ bosons produced by antiquarks have opposite polarization from those produced by quarks. The ratio of antiquark to quark production contribution from the antiquark and gluons is $\sim 10\%$.

The primary systematic uncertainties on asymmetry come from the unfolding procedure including the uncertainties from the event migration correction, the acceptance and efficiency correction, and the PDF inputs (fractional uncertainty, $[1.1-5.0] \times 10^{-3}$). To estimate the uncertainty from the PDF inputs, we determine the $Q(y_W, p_T^{W})$ correction with 45 CTETQ6.6 PDF sets, perform the measurement with different $Q(y_W, p_T^{W})$ [29], and extract the uncertainty for each $y_W$ bin using the prescription described in Ref. [21]. Other systematic uncertainties arise from the modeling of the $p_T^{W}$ distribution and the final state radiation modeling ($[0.1-2.4] \times 10^{-4}$), electron identification corrections ($[0.1-0.7] \times 10^{-3}$), electron energy modeling ($[0.1-0.5] \times 10^{-3}$), hadronic recoil modeling ($[0.1-0.8] \times 10^{-3}$), background modeling ($[0.1-1.0] \times 10^{-3}$), MC modeling imperfections ($[0.2-2.6] \times 10^{-3}$), electron charge misidentification ($[0.1-2.0] \times 10^{-3}$), and the relative efficiency for positrons and electrons ($K_{\text{eff}}$) ($[0.1-0.6] \times 10^{-3}$).

Figure 2 shows the measured values of the $W$ boson asymmetry together with the result from CDF [12]. The data are compared to the MC@NLO prediction with the NNPDF2.3 [30] PDF set, next-to-leading order RESBOS prediction with PHOTOS [31] using the CTEQ6.6 central PDF set, and MC@NLO using MSTW2008NLO [32] central PDF set. In the predictions, we require both the electron and neutrino transverse momentum to be above 25 GeV and merge the radiated photons into the electron if they fall within a cone of radius $\Delta R = \sqrt{2}$.

There is agreement between the data and predictions, although the predictions are systematically higher than the data by $\sim 1$ standard deviation in all measurements for $|y_W|$ between 0.1 and 1. Values of the asymmetry in bins of $y_W$, average bin positions, and predictions are shown in Table III. The experimental uncertainties are substantially smaller than the uncertainties from the NNPDF2.3 PDF sets in all $y_W$ bins, demonstrating the importance of this analysis to improve PDFs. Table III lists the correlations between central values in different $y_W$ bins that are introduced by the ambiguity in $p_T^{W}$. The correlation coefficients of systematic uncertainties between different $y_W$ are negligible.

In summary, we have measured the $W$ boson charge asymmetry in $p\bar{p} \rightarrow W \rightarrow e\nu$ events using data corresponding to 9.7 fb$^{-1}$ of integrated luminosity collected.
 uncertainties. The prediction comes from both the PDF uncertainties and statistical and the second is systematic. The uncertainties on resonbos with MC@NLO in percent (%) for each |

TABLE II: CP-folded W charge asymmetry for data and predictions from MC@NLO using NNPDF2.3 PDFs tabulated in percent (%) for each \(|y_W|\) bin. The \(|\langle y_W \rangle|\) is calculated as the cross section weighted average of \(y_W\) in each bin from resonbos with photos. For data, the first uncertainty is statistical and the second is systematic. The uncertainties on the prediction come from both the PDF uncertainties and \(\alpha_s\) uncertainties.

| Bin index | \(|y_W|\) | \(|\langle y_W \rangle|\) | Data | Prediction |
|----------|---------|----------------|------|-----------|
| 1        | 0.0–0.2 | 0.10           | 1.40 ± 0.17 ± 0.12 | 1.61 ± 0.19 |
| 2        | 0.2–0.4 | 0.30           | 4.32 ± 0.18 ± 0.19 | 5.06 ± 0.33 |
| 3        | 0.4–0.6 | 0.50           | 7.33 ± 0.19 ± 0.27 | 8.50 ± 0.41 |
| 4        | 0.6–0.8 | 0.70           | 10.59 ± 0.20 ± 0.32 | 12.05 ± 0.53 |
| 5        | 0.8–1.0 | 0.90           | 14.36 ± 0.21 ± 0.34 | 15.36 ± 0.66 |
| 6        | 1.0–1.2 | 1.10           | 18.32 ± 0.22 ± 0.37 | 18.86 ± 0.74 |
| 7        | 1.2–1.4 | 1.30           | 22.06 ± 0.24 ± 0.39 | 22.52 ± 0.80 |
| 8        | 1.4–1.6 | 1.50           | 25.74 ± 0.27 ± 0.36 | 26.30 ± 0.85 |
| 9        | 1.6–1.8 | 1.70           | 29.75 ± 0.31 ± 0.34 | 29.89 ± 0.92 |
| 10       | 1.8–2.0 | 1.90           | 34.46 ± 0.35 ± 0.38 | 34.04 ± 1.08 |
| 11       | 2.0–2.2 | 2.10           | 40.42 ± 0.40 ± 0.43 | 39.77 ± 1.31 |
| 12       | 2.2–2.4 | 2.29           | 47.55 ± 0.44 ± 0.43 | 47.73 ± 1.62 |
| 13       | 2.4–2.7 | 2.52           | 59.10 ± 0.46 ± 0.44 | 61.81 ± 1.74 |
| 14       | 2.7–3.2 | 2.81           | 77.33 ± 0.93 ± 0.56 | 78.05 ± 4.36 |

by the D0 experiment at \(\sqrt{s} = 1.96\) TeV. By using the neutrino weighting method, the most precise direct measurement of the W boson charge asymmetry to date is obtained. With coverage extended to \(|y'| = 3.2\), this measurement can be used to improve the precision and accuracy of next-generation PDF sets; in particular, it provides more accurate information for PDFs at high \(x\), compared with measurements of the lepton charge asymmetry, which is crucial for many beyond SM searches.

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| $|y_W|$ bin | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13  | 14  |
|----------|----|----|----|----|----|----|----|----|----|----|----|----|-----|-----|
| 1        | 1.00 0.84 0.57 0.38 0.29 0.25 0.21 0.16 0.10 0.06 0.04 0.03 0.02 0.01 |
| 2        | 1.00 0.85 0.58 0.39 0.29 0.24 0.16 0.10 0.06 0.05 0.04 0.03 0.02 |
| 3        | 1.00 0.85 0.58 0.38 0.26 0.16 0.10 0.06 0.05 0.06 0.05 0.03 |
| 4        | 1.00 0.83 0.52 0.29 0.16 0.09 0.07 0.08 0.10 0.09 0.06 |
| 5        | 1.00 0.78 0.42 0.19 0.11 0.10 0.13 0.15 0.14 0.10 |
| 6        | 1.00 0.74 0.37 0.22 0.19 0.22 0.20 0.15 |
| 7        | 1.00 0.76 0.50 0.38 0.34 0.31 0.29 0.21 |
|          | 1.00 0.84 0.62 0.47 0.38 0.34 0.27 |
| 9        | 1.00 0.87 0.65 0.48 0.40 0.31 |
| 10       | 1.00 0.89 0.67 0.51 0.36 |
| 11       | 1.00 0.89 0.66 0.41 |
| 12       | 1.00 0.86 0.45 |
| 13       | 1.00 0.50 |
| 14       | 1.00 |

[17] D0 uses a cylindrical coordinate system with the z axis along the beam axis in the proton direction. Angles $\theta$ and $\phi$ are the polar and azimuthal angles, respectively. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$ where $\theta$ is measured with respect to the interaction vertex. In the massless limit, $\eta$ is equivalent to the rapidity $y = (1/2) \ln[(E+p_z)/(E-p_z)]$, and $\eta_{det}$ is the pseudorapidity measured with respect to the center of the detector.