

Measurement of the Electron Charge Asymmetry in $p\bar{p} \rightarrow W + X \rightarrow e\nu + X$ Events at $\sqrt{s} = 1.96$ TeV

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We present a measurement of the electron 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 0.75 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron Collider. The asymmetry is measured as a function of the electron transverse momentum and pseudorapidity in the interval $(-3.2, 3.2)$ and is compared with expectations from next-to-leading order calculations in perturbative quantum chromodynamics. These measurements will allow more accurate determinations of the proton parton distribution functions.

In $p\bar{p}$ collisions, $W^+(W^-)$ bosons are produced primarily by the annihilation of $u(d)$ quarks in the proton with $\bar{d}(\bar{u})$ quarks in the antiproton. The probability of finding a parton carrying momentum fraction x of the proton can be expressed by parton distribution functions (PDFs). Any difference between the u - and d -quark PDFs will result in an asymmetry in the W boson rapidity distribution between W^+ and W^- boson production [1]. In this Letter, we present a measurement of the charged lepton asymmetry with much larger statistical precision and over a wider kinematic range than previous measurements [2,3]. This information provides constraints on the ratio of u - and d -quark PDFs, $u(x)/d(x)$. PDFs are necessary inputs for cross section calculations at hadron colliders. Many measurements have significant uncertainties associated with the accuracy of the PDFs; therefore, understanding the PDFs is extremely important. Throughout this Letter, we use the notation “electron” to mean “electron and positron,” unless specified otherwise.

We detect W bosons via the direct decay $W \rightarrow e\nu$. The boson rapidity (y_W) cannot be measured due to the unknown longitudinal momentum of the neutrino. We instead measure the electron charge asymmetry, which is a convolution of the W boson production asymmetry and the parity violating asymmetry from the W boson decay. Since the V - A interaction is well understood, the lepton charge asymmetry retains sensitivity to the underlying W boson asymmetry. The electron charge asymmetry ($A(\eta^e)$) is defined as:

$$A(\eta^e) = \frac{d\sigma^+/d\eta^e - d\sigma^-/d\eta^e}{d\sigma^+/d\eta^e + d\sigma^-/d\eta^e}, \quad (1)$$

where η^e is the pseudorapidity of the electron [4] and $d\sigma^+/d\eta^e$ ($d\sigma^-/d\eta^e$) is the differential cross section for the electrons from W^+ (W^-) bosons as a function of the electron pseudorapidity. When the detection efficiencies and acceptances for positrons and electrons are identical, the asymmetry becomes the difference in the number of positron and electron events over the sum.

In this Letter, we present results obtained from more than twice the integrated luminosity of previous measurements by the CDF [2] and D0 [3] collaborations and extend the measurement for leptons with $|\eta^\ell| < 3.2$, compared to $|\eta^\ell| < 2.5$ for CDF and $|\eta^\ell| < 2.0$ for the previous D0 measurement. By extending to higher rapidity leptons, we can provide information about the PDFs for a broader x range ($0.002 < x < 1.0$ for $|y_W| < 3.2$) at high $Q^2 \sim M_W^2$, where Q^2 is the momentum transfer squared and M_W is the W boson mass.

The data sample used in this measurement was collected with the D0 detector [5] at the Fermilab Tevatron Collider using a set of inclusive single-electron triggers based only on calorimeter information [6]. The integrated luminosity is $750 \pm 46 \text{ pb}^{-1}$ [7].

The D0 detector includes a central tracking system, composed of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet and covering pseudorapidities of $|\eta_D| < 3.0$ and $|\eta_D| < 2.5$, respectively [4]. Three liquid argon and uranium calorimeters provide coverage out to $|\eta_D| \approx 4.2$: a central section (CC) with coverage of $|\eta_D| < 1.1$ and two end calorimeters (EC) with a coverage of $1.5 < |\eta_D| < 4.2$.

W boson candidates are identified by one isolated electromagnetic cluster accompanied by large missing transverse energy (\cancel{E}_T). \cancel{E}_T is determined by the vector sum of the transverse components of the energy deposited in the calorimeter and the transverse momentum (E_T) of the electron. Electron candidates are further required to have shower shapes consistent with that of an electron. The E_T of the electron and the \cancel{E}_T are required to be greater than 25 GeV. Additionally, the transverse mass M_T of the electron and \cancel{E}_T is required to be greater than 50 GeV, where $M_T = \sqrt{2E_T\cancel{E}_T(1 - \cos\Delta\phi)}$, and $\Delta\phi$ is the azimuthal angle between the electron and \cancel{E}_T .

Electrons are required to fall within the fiducial region of the calorimeters, and must be spatially matched to a reconstructed track in the central tracking system. Because of the different geometrical coverage of the calorimeters and the tracker, the electrons are divided into four different types depending on the locations of the electrons in the calorimeter and the associated track polar angle and the collision vertex: CC electrons within the full coverage of the CFT, EC electrons within the full coverage of the CFT, EC electrons within the partial coverage of the CFT, and EC electrons outside the coverage of the CFT. Optimized choices for selection criteria are established for each type. SMT hits are required in all four types, with tracks outside the CFT fiducial region requiring at least nine SMT hits. A total of 491 250 events satisfy the selection, with 358 336 events with electrons in the CC and 132 914 events with electrons in the EC. The charge asymmetry is measured in 24 electron pseudorapidity bins for $|\eta^e| < 3.2$.

The asymmetry measurement is sensitive to misidentification of the electron charge. We measure the charge misidentification rate with $Z \rightarrow ee$ events using a “tag-and-probe” method [7] where a track matched to one electron tags the charge of the other. Tight conditions are applied on the tag electron to make sure its charge is correctly determined. The rate ranges from 0.2% at $|\eta^e| \approx 0$ to 9% at $|\eta^e| \approx 3$. The absolute uncertainty in the charge misidentification changes from 0.1% to 2.6% depending on the electron pseudorapidity, and is dominated by the statistics of the Z boson sample.

Sources of charge bias in the event selection are investigated by studying $Z \rightarrow ee$ events. All selection efficiencies are measured for electrons and positrons separately, and no charge dependent biases in acceptance or efficiencies are found. To reduce any possible residual charge

determination biases due to instrumental effects, the direction of the magnetic field in the solenoidal magnet was regularly reversed. Approximately 46% of the selected W bosons were collected with the solenoid at forward polarity, and 54% at reverse polarity. The charge asymmetry is measured separately for each solenoid polarity and no significant differences are observed.

Three sources of background can dilute the charge asymmetry: $Z \rightarrow ee$ events where one electron is not detected by the calorimeter, $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ events, and multijet events in which one jet is misidentified as an electron and a large \cancel{E}_T is produced by fragmentation fluctuations or misreconstruction. The $A(\eta^e)$ values are corrected for the backgrounds in each bin.

Events with electrons from $Z \rightarrow ee$ and $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ decays exhibit charge asymmetries, and these two background contributions are evaluated using Monte Carlo (MC) events generated with PYTHIA [8] and processed with a detailed detector simulation based on GEANT [9]. The fractions of $Z \rightarrow ee$ and $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ events estimated to contribute to the candidate sample are $(1.3 \pm 0.1)\%$ and $(2.1 \pm 0.1)\%$, respectively.

The background fraction from multijet events is estimated by starting from a sample of candidate events with loose shower shape requirements and then selecting a subset of events which satisfy the final tighter requirement. From $Z \rightarrow ee$ events, and a sample of multijet events passing the preselection but with low \cancel{E}_T , we determine the probabilities with which real and fake electrons will pass the final shower shape requirement. These two prob-

abilities (verified to be charge symmetric), along with the number of events selected in the loose and tight samples allow us to calculate the fraction of multijet events within our final selection. The final background contamination from multijet events is estimated to be $(0.8 \pm 0.4)\%$.

The final charge asymmetry is corrected for electron energy scale and resolution, \cancel{E}_T resolution and trigger efficiency. The correction is estimated by comparing the asymmetry from the generator level PYTHIA $W \rightarrow e\nu$ MC calculations to the GEANT-simulated results for each electron type.

The electron charge asymmetry is determined separately for each electron pseudorapidity bin and for each of the four electron types and then combined. The charge misidentification and background estimations are performed

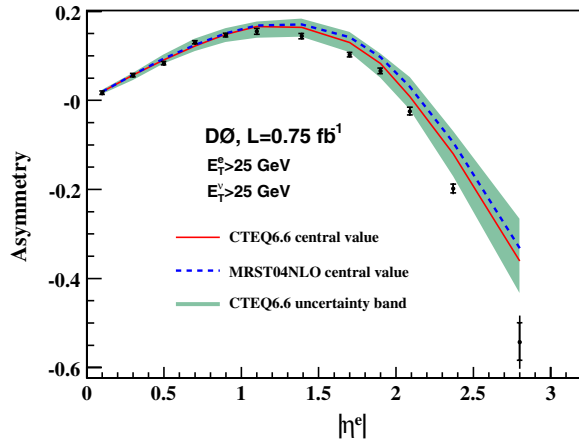


FIG. 1 (color online). The folded electron charge asymmetry distribution. The horizontal bars show the statistical uncertainty and the full vertical lines show the total uncertainty on each point. The total uncertainty is the sum in quadrature of the statistical and systematic uncertainties. The solid (dashed) line is the theoretical prediction for the asymmetry using the CTEQ6.6 (MRST04NLO) central PDF set. The shaded band is the uncertainty band determined using the 44 CTEQ6.6 PDF uncertainty sets. All three were determined using RESBOS with PHOTOS.

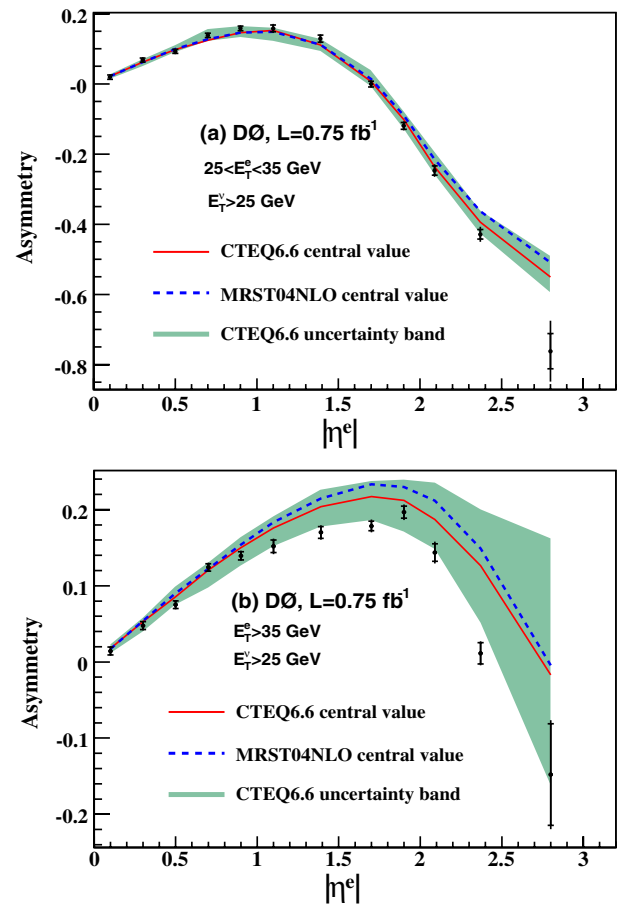


FIG. 2 (color online). The folded electron charge asymmetry distribution in two electron E_T bins: $25 < E_T < 35$ GeV for (a) and $E_T > 35$ GeV for (b). In each plot, the horizontal bars show the statistical uncertainty and the full vertical lines show the total uncertainty on each point. The total uncertainty is the sum in quadrature of the statistical and systematic uncertainties. The solid (dashed) line is the theoretical prediction for the asymmetry using the CTEQ6.6 (MRST04NLO) central PDF set. The shaded band is the uncertainty band determined using the 44 CTEQ6.6 PDF uncertainty sets. All three were determined using RESBOS with PHOTOS.

TABLE I. Folded electron charge asymmetry for data and predictions from RESBOS with PHOTOS using CTEQ6.6 PDFs tabulated in percent. $\langle |\eta^e| \rangle$ is the cross section weighted average of electron pseudorapidity in each bin from RESBOS with PHOTOS. For data, the first uncertainty is statistical and the second is systematic. For the predictions, the uncertainties are from the PDFs only.

| η^e region | $\langle \eta^e \rangle$ | $E_T > 25$ GeV | | $A(\eta^e)$ $25 < E_T < 35$ GeV | | $E_T > 35$ GeV | |
|-----------------|----------------------------|-------------------------|-----------------------|--------------------------------------|-----------------------|-------------------------|------------------------|
| | | Data | Prediction | Data | Prediction | Data | Prediction |
| 0.0–0.2 | 0.10 | $1.6 \pm 0.4 \pm 0.3$ | $1.9^{+0.4}_{-0.5}$ | $1.9 \pm 0.6 \pm 0.5$ | $2.1^{+0.5}_{-0.8}$ | $1.4 \pm 0.5 \pm 0.4$ | $1.8^{+0.5}_{-0.7}$ |
| 0.2–0.4 | 0.30 | $5.6 \pm 0.4 \pm 0.3$ | $5.7^{+0.4}_{-1.2}$ | $6.8 \pm 0.6 \pm 0.5$ | $6.2^{+0.8}_{-1.3}$ | $4.8 \pm 0.5 \pm 0.4$ | $5.3^{+0.5}_{-1.3}$ |
| 0.4–0.6 | 0.50 | $8.2 \pm 0.4 \pm 0.3$ | $9.1^{+1.2}_{-0.9}$ | $9.3 \pm 0.6 \pm 0.5$ | $9.8^{+1.2}_{-0.8}$ | $7.5 \pm 0.5 \pm 0.4$ | $8.5^{+1.3}_{-1.1}$ |
| 0.6–0.8 | 0.70 | $13.0 \pm 0.4 \pm 0.3$ | $12.2^{+1.5}_{-1.2}$ | $13.8 \pm 0.6 \pm 0.5$ | $12.4^{+3.1}_{-0.3}$ | $12.4 \pm 0.5 \pm 0.4$ | $12.1^{+1.0}_{-2.3}$ |
| 0.8–1.0 | 0.90 | $14.6 \pm 0.4 \pm 0.3$ | $14.8^{+1.3}_{-1.8}$ | $15.8 \pm 0.7 \pm 0.6$ | $14.6^{+1.7}_{-1.3}$ | $13.9 \pm 0.5 \pm 0.4$ | $15.0^{+1.3}_{-2.4}$ |
| 1.0–1.2 | 1.10 | $15.5 \pm 0.6 \pm 0.5$ | $16.6^{+1.0}_{-2.5}$ | $15.8 \pm 1.0 \pm 0.8$ | $15.2^{+0.7}_{-3.0}$ | $15.2 \pm 0.8 \pm 0.6$ | $17.6^{+1.5}_{-2.4}$ |
| 1.2–1.6 | 1.39 | $14.4 \pm 0.6 \pm 0.5$ | $16.4^{+1.8}_{-2.2}$ | $12.9 \pm 1.0 \pm 0.8$ | $11.1^{+1.8}_{-1.8}$ | $17.0 \pm 0.8 \pm 0.6$ | $20.4^{+2.2}_{-2.6}$ |
| 1.6–1.8 | 1.70 | $10.2 \pm 0.5 \pm 0.4$ | $13.0^{+2.3}_{-2.2}$ | $-0.1 \pm 0.8 \pm 0.6$ | $0.7^{+3.2}_{-1.3}$ | $17.9 \pm 0.6 \pm 0.6$ | $21.7^{+2.0}_{-3.1}$ |
| 1.8–2.0 | 1.90 | $6.6 \pm 0.6 \pm 0.5$ | $8.3^{+2.2}_{-3.3}$ | $-12.0 \pm 1.0 \pm 0.8$ | $-10.1^{+2.2}_{-2.7}$ | $19.7 \pm 0.8 \pm 0.7$ | $21.2^{+2.7}_{-4.1}$ |
| 2.0–2.2 | 2.09 | $-2.5 \pm 0.9 \pm 0.6$ | $0.9^{+4.8}_{-3.0}$ | $-24.7 \pm 1.3 \pm 1.2$ | $-23.6^{+4.1}_{-2.2}$ | $14.4 \pm 1.2 \pm 0.9$ | $18.7^{+4.8}_{-3.9}$ |
| 2.2–2.6 | 2.37 | $-19.8 \pm 1.0 \pm 0.7$ | $-12.0^{+5.1}_{-5.1}$ | $-42.9 \pm 1.4 \pm 1.6$ | $-39.4^{+3.2}_{-3.3}$ | $1.1 \pm 1.4 \pm 0.7$ | $12.6^{+7.4}_{-7.5}$ |
| 2.6–3.2 | 2.80 | $-54.3 \pm 4.2 \pm 4.2$ | $-36.1^{+9.4}_{-7.2}$ | $-76.2 \pm 5.0 \pm 7.1$ | $-55.1^{+6.0}_{-4.3}$ | $-14.8 \pm 6.7 \pm 2.6$ | $-1.7^{+17.9}_{-14.4}$ |

independently for each of these measurements. Assuming $A(-\eta^e) = -A(\eta^e)$ due to CP invariance, we fold the data to increase the available statistics and obtain a more precise measurement of $A(\eta^e)$.

Figure 1 shows the folded electron charge asymmetry. The dominant sources of systematic uncertainties originate from the estimation of charge misidentification and multi-jet backgrounds. The bin-by-bin correlations of these systematic uncertainties are negligible. Also shown in Fig. 1 are the theoretical predictions obtained using the RESBOS event generator [10] (with gluon resummation at low boson p_T and next-to-leading order (NLO) perturbative QCD calculations at high boson p_T) with PHOTOS [11] (for QED final state radiation). The PDFs used to generate these predictions are the CTEQ6.6 NLO PDFs [12] and MRST04NLO PDFs [13]. Theoretical uncertainties derived from the 44 CTEQ6.6 PDF uncertainty sets are also shown. These curves are generated by applying a 25 GeV cut on the electron and neutrino generator-level transverse momenta. The asymmetric PDF uncertainty band is calculated using the formula described in Ref. [14].

We also measure the asymmetry in two bins of electron E_T : $25 < E_T < 35$ GeV and $E_T > 35$ GeV. For a given η^e , the two E_T regions probe different ranges of y_W and thus allow a finer probe of the x dependence. The folded electron charge asymmetries, along with the theoretical predictions, for the two E_T bins are shown in Fig. 2.

The measured values of the asymmetry and uncertainties, together with the CTEQ6.6 predictions, for $E_T > 25$ GeV and the two separate E_T bins are listed in Table I. The measured charge asymmetries tend to be lower than the theoretical predictions using both the CTEQ6.6

and MRST04NLO central PDF sets for high pseudorapidity electrons. For most η^e bins, the experimental uncertainties are smaller than the uncertainties given by the most recent CTEQ6.6 uncertainty sets, demonstrating the sensitivity of our measurement.

A complete interpretation of the impact of these data on the PDFs will require revised NLO QCD fits to all available data. However, we can estimate the impact of this measurement by investigating the behavior of the $u(x)/d(x)$ ratio at $Q^2 = M_W^2$ for the 44 CTEQ6.6 PDF uncertainty sets. We observe that they differ by 10%–20% for $x > 0.2$, which illustrates the current limited knowledge on this ratio at high x . We find that the sets which best match our data consistently correspond to $u(x)/d(x)$ ratios which lie below the central prediction by 5%–10% for $x > 0.2$, while those with the worst agreement lie above the central prediction by a similar amount. We conclude that our data favor smaller $u(x)/d(x)$ ratios at high x .

In summary, we have measured the charge asymmetry of electrons in $p\bar{p} \rightarrow W + X \rightarrow e\nu + X$ using 0.75 fb^{-1} of data. The electron coverage is extended to $|\eta^e| < 3.2$ and the asymmetry is measured for electron $E_T > 25$ GeV, as well as two separate E_T bins to improve sensitivity to the PDFs. This measurement is the most precise electron charge asymmetry measurement to date, and the experimental uncertainties are smaller than the theoretical uncertainties across almost all electron pseudorapidities. Our result can be used to improve the precision and accuracy of next generation PDF sets, and will help to reduce the PDF uncertainty for high precision M_W measurements and also improve the predictions for the Higgs boson production at the hadron colliders.

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