

Charge Asymmetry in W -Boson Decays Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Charge asymmetry has been measured using 19 039 W decays recorded by the Collider Detector at Fermilab during the 1992–93 run of the Tevatron Collider. The asymmetry is sensitive to the ratio of d and u quark distributions to $x < 0.01$ at $Q^2 \approx M_W^2$, where nonperturbative effects are minimal. It is found that of the two current sets of parton distributions, those of Martin, Roberts, and Stirling are favored over the sets most recently produced by the CTEQ Collaboration. The W asymmetry data provide stronger constraints on d/u ratio than the recent measurements of $F_2^{\mu n}/F_2^{\mu p}$, which are limited by uncertainties originating from deuteron corrections.

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The previous study of the W asymmetry performed using the Collider Detector at Fermilab (CDF) 1988–89 data [1], with less than a quarter of the $\approx 20 \text{ pb}^{-1}$ available for the current analysis, indicated the potential for hadron collider data to contribute to our understanding of parton distribution functions (PDFs). Typically these distributions are extracted from deep inelastic scattering (DIS) data. These DIS experiments measure cross sections for electron, muon, or neutrino scattering off nucleon and nuclear targets over some range of x and Q^2 . The PDFs are extracted by fitting these data, within the framework of perturbative QCD, for the momentum distributions of the proton's constituent quarks and gluons. These functions are evolved to high Q^2 and used as input to virtually every hadronic cross section calculation. At CDF this fact implies that uncertainties in the PDFs translate into uncertainties in everything from a top-quark cross section to a W -boson mass measurement; there-

fore it is imperative that these distributions are well determined. In particular, the ratio of d and u quark distributions is usually extracted from data on the ratio of electron and muon scattering from neutrons and protons. Such data suffer from uncertainties in corrections due to deuteron binding effects [2] and also from unknown higher twist and nonperturbative effects [3] at low values of Q^2 . This Letter describes new data which significantly constrain the u and d quark momentum distributions in the nucleon.

W^+ (W^-) bosons are produced in $p\bar{p}$ collisions primarily by the annihilation of u (d) quarks from the proton and \bar{d} (\bar{u}) quarks from the antiproton. As the u quark tends to carry a larger fraction of the proton's momentum than the d quark, the W^+ (W^-) is boosted, on average, in the proton (antiproton) direction. The charge asymmetry in the production of W 's, as a function of rapidity (y_W), is therefore related to the difference in the u and d quark

distributions at very high Q^2 ($\approx M_W^2$) and low x ($0.007 < x < 0.24$) for $\sqrt{s} = 1.8$ TeV and $-1.8 < y_W < 1.8$.

The W decay involves a neutrino, whose longitudinal momentum is undetermined. Therefore the quantity measured is the charge asymmetry of the decay leptons, which has an added contribution due to the $V - A$ decay of the W . This portion of the asymmetry has been well measured by muon decay experiments [4]; thus in comparison to theory, one can attribute any deviations (between prediction and measurement) to the PDFs used in the calculations. The asymmetry is defined as

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

where $d\sigma^+$ ($d\sigma^-$) is the cross section for W^+ (W^-) decays to leptons as a function of lepton rapidity (y_l), with positive rapidity being defined in the proton beam direction. As long as the acceptance and efficiencies for detecting l^+ and l^- are equal, this ratio of cross sections becomes simply the difference in the number of l^+ and l^- over the sum; all efficiencies and the acceptance as well as the luminosity cancel. Further, by CP invariance, the asymmetry at positive y_l is equal in magnitude and opposite in sign to that at negative y_l , so the two values are combined reducing the effect of any differences in the efficiencies for l^+ and l^- .

The CDF is described in detail elsewhere [5]. W -boson decays to leptons are identified by the presence of a large amount of missing transverse energy (\cancel{E}_T) [6], accompanied by a track in the central tracking chamber (CTC) which points at either hits in the muon chambers or a cluster of energy in the electromagnetic (EM) calorimeters. The CTC is an 84 layer drift chamber which is immersed in a 1.4 T axial magnetic field. This magnetic field enables lepton charge determination, from the curvature of the track, to a high degree of certainty. Electron candidates are required to fall within the fiducial regions of either the central, $|y| < 1.1$, or the plug, $1.1 < |y| < 2.4$, EM calorimeters and to pass identification cuts based on the EM shower's profile determined with test beam electrons. Muon candidates are required to have a track in the muon tracking system, in addition to a minimum ionizing particle signal in the hadronic and EM calorimeters traversed by the muon track. The curvature (C) of the track is required to be well measured, $C/\delta C > 2$, and the track must pass within 2 mm of the beam line to reject cosmic rays as well as poorly measured tracks. Events are required to have a well defined vertex within 60 cm of the center of the detector, and $(\cancel{E}_T) > 25$ GeV (in the case of muons after correcting for the muon's momentum). The transverse energy (E_T) of the lepton is required to be greater than 25 GeV. To reduce the backgrounds due to misidentified dijets, events with a jet [7] whose E_T exceeds 20 GeV are rejected. The limiting factor in y for this measurement is the rapidity coverage provided by the CTC. The data are divided into three

samples: central electrons, plug electrons, and central muons.

The triggers for the central electron and muon data sets are checked for any charge or E_T dependence using data from independent triggers. No evidence of such dependences is found. The plug electron triggers, while not having any charge dependence, are not fully efficient at 25 GeV. Therefore, a correction is determined on a bin by bin basis, using a Monte Carlo calculation and the measured trigger efficiency, and applied to the plug electron data. The correction to $A(y_l)$ is found to be less than 0.005.

Sources of a charge bias in the event selection are investigated by selecting high E_T electrons or muons, from either a sample of Z 's or a sample of W 's, which satisfy tight kinematic constraints. No charge dependent effects are observed. For example [8], none of the 648 central-central Z 's or 332 central-plug Z 's have same sign leptons, implying an upper limit on the probability of misidentifying the lepton's charge of 0.48% and 0.9% in the central and plug regions, respectively, at the 90% confidence level (C.L.).

The backgrounds to the data (described below) are all typically small. In the plug electron sample, misidentified dijet events are the largest source of background. This background source is charge symmetric, so it acts to dilute the charge symmetry. The largest background in the central electron sample is due to $W^\pm \rightarrow \tau^\pm \nu \rightarrow e^\pm \nu \nu \nu$. For the central muon sample the largest background is misidentified $Z \rightarrow \mu^+ \mu^-$, where one of the muons is lost out the end of the CTC. Misidentified Z decays to electrons are negligible because the plug and forward calorimeters have a much larger geometric acceptance than do the muon chambers of the CTC. The $Z \rightarrow \tau^+ \tau^-$ contamination is also considered and found to be negligible in all three data sets. These vector boson related backgrounds are estimated using a Monte Carlo and detector simulation, and their charge asymmetries are likewise determined. The cosmic ray contamination of the muon data is negligible. The $A(y_l)$ values (shown in Fig. 1) are then corrected on a bin by bin basis for the backgrounds listed in Table I, taking into account the shape of each background's charge asymmetry [8]. The overall systematic uncertainty is very small (as shown in Fig. 2).

Figure 1 shows the uncorrected asymmetry before the values at positive y are combined with the opposite asymmetry at negative y . The level of agreement between the various detector types also indicates that systematic effects are indeed small. Also shown is the next-to-leading order (NLO) asymmetry predictions [9] made assuming standard W left and right handed couplings and that which is found when the couplings are allowed to go to their 90% C.L. limits [10]; both calculations use the Martin-Roberts-Stirling (MRS) D'_l parton distribution functions (PDFs) as input. Clearly the uncertainty in the W couplings is much smaller than the statistical error of the measurement.

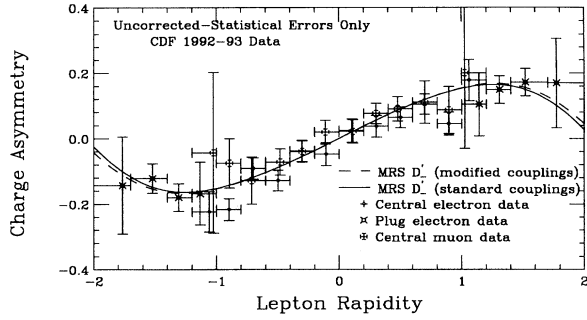


FIG. 1. The charge asymmetry before applying any corrections found in each of the detector types (central EM, plug EM, and central muon). Also shown (dashed line) is the effect of allowing the W couplings to go to their 90% C.L. limits.

Figure 2 shows the fully corrected asymmetry after taking the weighted mean of the various data sets and the $\pm y$ bins. The data are listed in Table II along with the total uncertainty as well as the average y_i of the leptons which contribute to each bin. Also shown are the NLO calculations [9] made using several sets of parton distributions [11] as input. *The $A(y_i)$ measurement was not included in any of these PDF determinations; therefore it provides an independent test of the PDFs.* To quantify the degree to which the various PDFs reproduce the data, Table III lists the results of χ^2 tests of the goodness of fit. There is no differentiating power in the first and last y bins. In particular, the last bin is statistically limited because the W production cross section is small at large y . Therefore the χ^2 is calculated for the seven bins spanning $0.2 < |y| < 1.7$ and for the weighted means of the bins (the theoretically calculated asymmetries were weighted in the identical manner). The motivation for the last test is that all the modern PDFs predict asymmetries with essentially the same shape and only differ in overall magnitude.

As can be seen in Table III, our data exclude the older MRS E', MRS B', and Morfin-Tung (MT) B1 distributions, which were extracted before the recent precision, high statistics DIS data were available. What is more significant is the extent to which the asymmetry data favor the recent MRS distributions (MRS D'_0 , MRS D'_L , and MRS H) over the most recent CTEQ2 distributions, as both groups had access to the same recent DIS data.

The W charge asymmetry is particularly sensitive to the slope of the d/u ratio versus x [12,13], whereas the

TABLE I. Backgrounds (%) in the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ charge asymmetry event samples. The values in boldface were used to correct the measurement in conjunction with the background's charge asymmetry.

Source	Central e	Plug e	Central μ
$W \rightarrow \tau\nu$	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2
QCD	0.4 ± 0.1	4.1 ± 0.9	0.3 ± 0.1
$Z \rightarrow ee$ or $\mu\mu$	<0.2	<0.2	4.7 ± 0.7
$Z \rightarrow \tau\tau$	<0.1	<0.1	<0.1

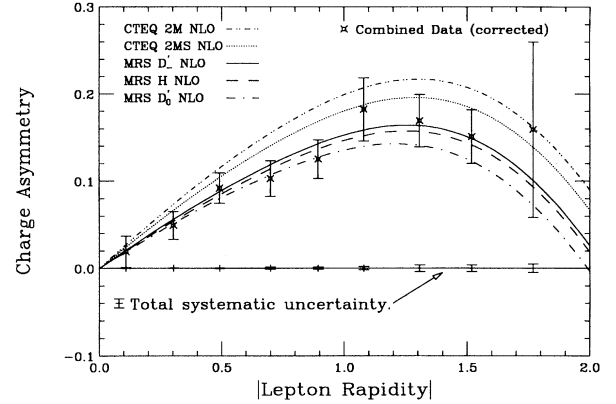


FIG. 2. The fully corrected charged asymmetry after the data from the various detectors are combined and folded about $y = 0$. The error bars along the x axis show the total systematic errors associated with each bin.

$F_2^{\mu n}/F_2^{\mu p}$ measurements are sensitive to the magnitude of this ratio as well as to the quantity $\bar{u} - \bar{d}$. Recently the New Muon Collaboration (NMC) has measured $F_2^{\mu n}/F_2^{\mu p}$ [14] over an x range comparable to that accessible at CDF (though at much lower Q^2). The NMC data [2,15] were used to constrain d/u in the most recent parton distribution fits. For easier comparison of the d/u slopes, Fig. 3(b) shows the d/u ratios after being shifted by a constant so they agree with MRS D'_0 at $x = 0.2$. The distributions which predict the largest average slope of the d/u ratio over the x range 0.007–0.24 also predict the largest charge asymmetry. One sees that even though the MRS and CTEQ PDFs were both determined by fitting to the $F_2^{\mu n}/F_2^{\mu p}$ data, they have very different d/u distributions and thus very different charge asymmetry predictions. This is because $F_2^{\mu n}/F_2^{\mu p}$ is also sensitive to the differences in the \bar{u} and \bar{d} distributions, whereas the $A(y_i)$ asymmetry is not as sensitive. CTEQ's parameterization of the \bar{u} and \bar{d} sea distributions compensates for a steep d/u ratio [16] and leads to a prediction for $F_2^{\mu n}/F_2^{\mu p}$ which is consistent with the NMC data but is much less consistent with the $A(y_i)$ measurement presented in this Letter.

TABLE II. The charge asymmetries (after all corrections) and total uncertainties in the combined e and μ channels.

$ y_i $ bin	$\langle y_i \rangle$	$A(y_i)$	σ
0.0–0.2	0.11	0.019	± 0.018
0.2–0.4	0.30	0.049	± 0.016
0.4–0.6	0.49	0.092	± 0.017
0.6–0.8	0.70	0.103	± 0.020
0.8–1.0	0.90	0.125	± 0.022
1.0–1.2	1.08	0.182	± 0.036
1.2–1.4	1.31	0.169	± 0.030
1.4–1.7	1.52	0.151	± 0.031
1.7–2.0	1.77	0.16	± 0.10

TABLE III. The χ^2 comparisons between the predicted asymmetries (calculated at NLO) for several NLO PDFs including the most recent MRS and CTEQ distributions. The comparison of the weighted means $\bar{A}(y_l)$ indicates the MRS H distributions fit the asymmetry data best. The very recent PDFs (CTEQ3 and MRS A) are not included in the comparison, since the CDF asymmetry data were included in these fits.

PDF set	$0.2 < y_l < 1.7$ χ^2 (7 DF)	$\mathcal{P}(\chi^E)$	$\Delta\sigma$	$\bar{A}(y_l)$ $\mathcal{P}(\sigma^E)$
CTEQ 2M	24	<0.01	4.6	<0.01
CTEQ 2MS	11	0.15	2.9	<0.01
CTEQ 2MF	17	0.02	3.8	<0.01
CTEQ 2ML	15	0.04	3.5	<0.01
CTEQ 1M	6.1	0.52	2.1	0.04
CTEQ 1MS	3.9	0.79	1.5	0.13
MT B1	17	0.02	-3.2	<0.01
MRS H	1.8	0.97	-0.1	0.96
MRS D'	1.9	0.97	0.5	0.61
MRS D'_0	3.6	0.83	-0.9	0.35
HMRS B	4.2	0.75	-1.2	0.23
HMRS B_0	19	0.01	-3.6	<0.01
MRS E'	30	<0.01	-4.9	<0.01
MRS B'	24	<0.01	-4.1	<0.01
GRV NLO	12	0.12	3.0	<0.01

In summary, the W charge asymmetry measurement from CDF is showing sensitivity to the slope of the d/u quark distribution at a level of precision which is already better than deep inelastic scattering experiments, which have additional uncertainties originating from unknown higher twist and nonperturbative effects [3] at low values of Q^2 , at small x , and also uncertainties in the extraction of neutron cross sections from deuterium data [2]. The uncertainty in the slope of the d/u quark distribution is the dominant contribution to the systematic error from PDFs in the extraction of the W mass from collider data. These new asymmetry measurements already can be used to substantially reduce the errors on the W mass [17]. The upcoming run, with its fourfold increase in integrated luminosity, promises to cut the uncertainties in half, as the $A(y_l)$ systematic errors are small.

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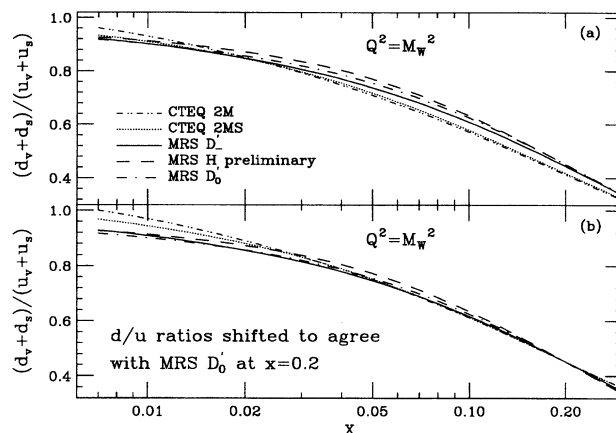


FIG. 3. (a) The d/u ratios for various parton distributions. (b) The d/u ratios of various PDFs after they have been shifted to agree with MRS D'_0 at $x = 0.2$; those which have the largest average slope predict the largest asymmetry.

are model dependent and it is not clear whether they should be applied to the data.

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