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

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The charge asymmetry of leptons from W-boson decay has been measured using $\bar{p}p$ data from the Collider Detector at Fermilab at $\sqrt{s}=1.8$ TeV. The observed asymmetry is well described by most of the available parton distributions.

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In this Letter, we use the rapidity distribution of leptons from decays of W particles produced in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV to extract information on parton momentum distributions at low x and high q^2. The 4.05-pb^{-1} data sample was collected by the Collider Detector at Fermilab (CDF) during the 1988–1989 Tevatron collider run.

In $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV, most of the W bosons are created by a valence-valence or valence-sea quark-antiquark interaction. Thus, a W^+ will be produced primarily by the interaction of a u quark from the proton and a $\bar{d}$ quark from the antiproton. Because u valence quarks in the proton have, on average, higher momentum than d valence quarks [1], a W^+ will tend to be boosted along the proton beam direction, and a W^- will be boosted along the antiproton direction. A measurement of the W^+ and W^- rapidity distributions (Y_W) in $\bar{p}p$ collisions gives useful information about parton distribution functions in the region of low x ($0.01<x<0.2$) and high q^2 ($\sim M_W^2$) where W's and Z's are produced [1].

There is a twofold ambiguity in reconstructing the W rapidity in a $W\to l\nu$ decay because the component of neutrino momentum along the beam direction is not measured. In our analysis, therefore, we measure the Y_W distribution indirectly via the charged lepton rapidity distribution. The charged lepton rapidity is the sum of the W rapidity and the lepton rapidity in the W rest frame, where the distribution of the latter quantity is given by $V-A$ couplings. It is convenient to measure the charge asymmetry of the leptons as a function of rapidity:

$$A(Y)\equiv\frac{d\sigma(l^+)/dY-d\sigma(l^-)/dY}{d\sigma(l^+)/dY+d\sigma(l^-)/dY}.$$

This asymmetry is insensitive to acceptance corrections if the detection efficiencies for both lepton charges are equal. Asymmetries at negative rapidity are, by CP invariance, equal in magnitude and opposite in sign to those at positive rapidity.

A brief description of the CDF follows [2]. Scintillator planes (BBC) located at small angles to both beam directions signal an inelastic $\bar{p}p$ collision. A vertex time-projection chamber (VTPC) measures the event vertex z position [3], and a central drift chamber inside of a 1.4-T solenoid precisely measures charged particle trajectories (tracks) and momenta. Calorimeters measure energy deposition in two depth segments, electromagnetic (EM) and hadronic (HAD). The calorimeters contain projective towers covering $|\eta|<4.2$, where $\eta\equiv-\ln[\tan(\theta/2)]$. The central calorimeters, $|\eta|<1.1$, use scintillator as the active medium; while the plug ($1.1<|\eta|<2.4$) and forward ($2.4<|\eta|<4.2$) calorimeters use gas proportional chambers. Proportional chambers near shower maximum (strip chambers) in the central EM calorimeter measure the position and shape of electromagnetic showers. The region $|\eta|<0.63$ is instrumented with drift chambers outside of the hadronic calorimeter for muon detection.

We use three types of W events, denoted by the type of lepton and the calorimeter section into which the lepton traveled: central electrons, central muons, and plug electrons. Trigger requirements are as follows. All events have to contain hits in both forward and backward BBC's. Central electron events contain at least one calorimeter energy cluster with EM transverse energy, E_T(EM), above 12 GeV, and with a ratio of hadronic to electromagnetic energy deposition (HAD/EM) less than 0.125, as well as a track pointing at the energy cluster with transverse momentum (P_T) greater than 6 GeV/c. Central muon events contain a track having $P_T>9.2$ GeV/c pointing to a central muon chamber track segment. Plug electron events contain a plug calorimeter energy cluster with $E_T(\text{EM})>23$ GeV and HAD/EM <0.125.

Events with isolated, well-measured leptons are selected from the three data sets by further requirements. Central electron events [4] are selected by requiring an energy cluster with $E_T(\text{EM})>20$ GeV away from the calorimeter edges so that energy is well measured, and a charged track pointing at the cluster with a ratio of energy to momentum (E/P) less than 1.5. The energy cluster is required to be consistent with an electron in several other ways, including the strip chamber profile in the z direction, the position match between the strip chamber and the track, the energy sharing between adjacent calorimeter towers, and the energy leakage into the hadronic calorimeter. In addition, the electron candidate is required to be isolated, i.e., the total transverse energy in a cone of radius 0.4 in η-ϕ space centered on the energy cluster cannot exceed the transverse energy of the electron candidate by more than 10%.

Central muon events are selected by requiring the track matching the muon chamber track segment to have $P_T > 20$ GeV/c, and no other track in the event to have $P_T > 15$ GeV/c. In addition, the transverse energy in a cone of radius 0.7 in η-ϕ space centered on the muon, including the towers traversed by the muon, must be less than 5 GeV, and the energy deposited in the towers traversed by the muon must be consistent with the approximately 2.5-GeV energy loss of a minimum ionizing track. Cosmic ray backgrounds are reduced by rejecting events with out-of-time or high momentum back-to-back tracks.

Plug electron events are selected by requiring an energy cluster in the plug calorimeter with $E_T(\mathrm{EM}) > 25$ GeV and HAD/EM < 0.05. The electron candidate is also required to be isolated as for central electrons, and the transverse shape of the cluster energy deposition must be consistent with an electromagnetic shower. Finally, we require detection of a majority of the hits expected in the VTPC along the vector between the event vertex and the plug cluster, and a track in the central drift chamber which matches the position of the energy cluster.

The $W \to l\nu$ decays are selected from these inclusive lepton samples by requiring large missing transverse energy ($\not{E}_T$) and large transverse mass [5] (M_T^W). We require $\not{E}_T > 20$ GeV for central electrons and $\not{E}_T > 25$ GeV for plug electrons, as well as $M_T^W > 50$ GeV/c^2 in the central electron and muon samples and $M_T^W > 60$ GeV/c^2 in the plug electron sample. The higher M_T^W cut in the plug sample is chosen to reduce the effect of the transverse energy trigger threshold on the analysis.

To ensure full energy containment for the $\not{E}_T$ measurement, we also require the collision point for each event to lie within 60 cm from the detector center. Cosmic ray contamination in the central muon sample is reduced by requiring $M_T^W < 90$ GeV/c^2. Events which contain an additional electron or muon candidate and are consistent with $Z^0 \to e^+e^-$ or $Z^0 \to \mu^+\mu^-$ decays are removed. Finally, we require that there be no "jets" [6] in the events with $E_T > 10$ GeV. This reduces the level of background as well as the effect of QCD W+multijet corrections to the leading-order predictions.

The final data sample contains 1605 central electron events, 800 central muon events [7], and 262 plug electron events [8]. The numbers of W events of each sign of charge in each rapidity bin are listed in Table I.

TABLE I. Raw numbers of W events of each charge and lepton rapidity interval [9].

$\|Y\|$	$+Q/+Y$	$-Q/-Y$	$+Q/-Y$	$-Q/+Y$	Total
		Central electrons			
0.0–0.2	54	73	63	71	261
0.2–0.4	83	82	68	82	315
0.4–0.6	98	109	78	82	367
0.6–0.8	104	96	85	64	349
0.8–1.0	70	72	46	62	250
1.0–1.2	15	18	15	15	63
		Central muons			
0.0–0.2	68	45	66	40	229
0.2–0.4	83	83	65	73	294
0.4–0.6	64	85	45	48	242
0.6–0.8	13	8	6	8	35
		Plug electrons			
1.3–1.7	101	60	50	51	262

A number of studies, using W samples, Monte Carlo events, cosmic ray events, and inclusive muon events, have verified that the reconstruction efficiencies are the same for both lepton charges. An additional uncertainty arises for plug electrons because at low angles the tracking momentum resolution is degraded and it is possible to make an incorrect charge determination. A Monte Carlo study shows that this effect is negligible. One cross-check is to look at $Z^0 \to e^+e^-$ events in which the charge of a central electron determines the charge of the other, plug electron. All 27 such events have the plug electron charge correctly assigned.

Background from QCD jet production, which dilutes the asymmetry, is estimated at $(0.7 \pm 0.3)\%$ for central

TABLE II. Measured W asymmetry values.

$\|Y\|$ Range	Asymmetry
Central electrons	
0.0–0.2	-0.027 ± 0.064
0.2–0.4	0.050 ± 0.058
0.4–0.6	0.131 ± 0.054
0.6–0.8	0.150 ± 0.055
0.8–1.0	0.141 ± 0.065
1.0–1.2	0.052 ± 0.128
Central muons	
0.0–0.2	0.029 ± 0.069
0.2–0.4	0.099 ± 0.058
0.4–0.6	0.241 ± 0.065
0.6–0.8	0.214 ± 0.172
Plug electrons	
1.3–1.7	0.223 ± 0.066

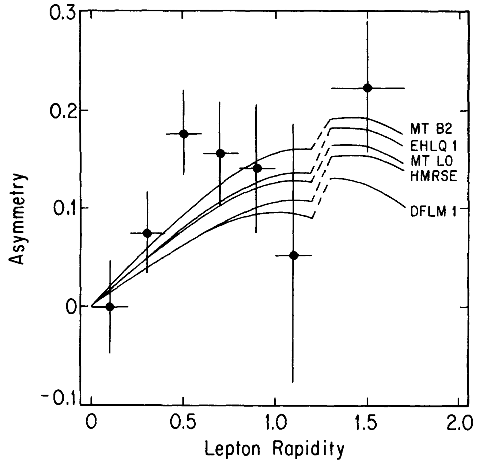

FIG. 1. Lepton asymmetries in $W \rightarrow l\nu$ events. The curves shown, which are predictions of representative parton distributions coupled to a leading-order calculation, are discontinuous because of the use of different transverse mass cuts in the central and plug regions (50 and 60 GeV/c^2, respectively).

TABLE III. A statistical comparison of W asymmetry data with leading-order predictions of various parton distribution sets. There are 7 degrees of freedom.

Function set	χ^2	Prob(χ^2)
MT B2	5.5	0.60
MT S2S	6.4	0.50
MT E1	6.4	0.49
MT S2M	6.4	0.49
EHLQ1	7.4	0.39
HMRSB	7.5	0.38
MT S1	7.9	0.34
MTLO	8.2	0.31
MT S1M	8.8	0.27
MT B1	9.1	0.25
EHLQ2	9.9	0.19
HMRSE	11.6	0.12
DFLM3	12.0	0.10
DFLM2	12.3	0.09
DFLM1	12.8	0.08

electrons, $(0.7 \pm 0.7)\%$ for central muons, and $(2.4 \pm 1.3)\%$ for plug electrons. The $(\leq 3\%)$ backgrounds from $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ sequential decays have the same asymmetry as the signal except for a very small $(\sim 3\times 10^{-4})$ correction due to the transverse mass cuts. These and other $(Z^0 \rightarrow e^+e^-, \mu^+\mu^-$, and $\tau^+\tau^-)$ backgrounds modify our observed asymmetries by less than 0.01 in all cases.

The asymmetry depends somewhat on transverse mass because as the transverse mass increases, the lepton rapidity becomes closer to the parent W rapidity. In the plug electron sample, a -0.011 correction is applied to the observed asymmetry because of reduced trigger efficiency for events with M_T^W close to the 60 GeV/c^2 threshold, in order to simulate a sharp M_T^W threshold for comparison with predictions.

Measured asymmetry values are listed in Table II. We quote the statistical combination of the asymmetry at positive rapidity with the negative of the asymmetry at negative rapidity, using the fact that the lepton asymmetry is, as mentioned earlier, an odd function of rapidity. Statistical and (small, ~ 0.01) systematic uncertainties have been added in quadrature. The systematic uncertainty is dominated by our determination of equal reconstruction efficiencies for positively and negatively charged leptons. These results, combining the central muon and electron data points, are shown in Fig. 1, along with the predictions of some representative parton distributions coupled to a leading-order calculation. The calculation assumes normal left-handed couplings at W production and decay vertices. Curves for the plug electron data are higher because of the higher transverse mass cut.

The degree of consistency between leading-order asymmetry calculations and these data is tested by calculating χ^2 between the seven data points and the calculated asymmetry values, for each of a number of parton distribution sets (EHLQ [10], DFLM [11], HMSR [12], and MT [13]). The χ^2 values and their probabilities are listed in Table III. As can be seen from Fig. 1, those parton distribution sets which predict larger asymmetries fit the data well. Among these are the parton distribution sets which use recent deep inelastic scattering data [12,13], and have ratios of d to u quark distributions, $d(x)/u(x)$, which fall more steeply with x.

The effect of higher-order $W+1$ jet diagrams on lepton asymmetry predictions has been investigated with the PAPAGENO Monte Carlo program [14]. The asymmetry is observed to increase by up to 0.02, depending on rapidity. Recently, a more complete next-to-leading logarithm calculation has been made with cuts designed to simulate our experimental cuts [15]. This order-α_s calculation in fact predicts asymmetries which are slightly *smaller* (by 0.02 at $Y=1$) than the leading-order predictions.

In summary, we have measured lepton asymmetries in a large sample of $W \rightarrow l\nu$ decays. The asymmetries, although on the high side of expectations, are consistent with predictions of many of the available parton distribution sets, particularly those which use recent deep inelastic scattering data.

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[6] The electron/muon candidate itself is excluded. Jet clusters used a cone size of $R=(\Delta\eta^2+\Delta\phi^2)^{1/2}=0.7$. A cluster of 10 GeV corresponds roughly to a parton E_T of 14 GeV. For details, see F. Abe *et al.*, Phys. Rev. Lett. **62**, 613 (1989).
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