Implication of $W$-boson Charge Asymmetry Measurements in $p\bar{p}$ Collisions for Models of Charge Symmetry Violations in Parton Distributions

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A surprisingly large charge symmetry violation of the sea quarks in the nucleon has been proposed in a recent article by Boros et al. as an explanation of the discrepancy between neutrino (CCFR) and muon (NMC) nucleon structure function data at low $x$. We show that these models are ruled out by the published CDF $W$ charge asymmetry measurements, which strongly constrain the ratio of $d$ and $u$ quark momentum distributions in the proton over the $x$ range of 0.006 to 0.34. This constraint also limits the systematic error from possible charge symmetry violation in the determinations of $\sin^2 \theta_W$ from $\nu N$ scattering experiments.

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In a recent Physical Review Letter [1], Boros et al. proposed a model in which a substantial charge symmetry violation (CSV) for parton distributions in the nucleon accounts for the experimental discrepancy between neutrino (CCFR) and muon (NMC) nucleon structure function data at low $x$. Charge symmetry (sometimes also referred to as isospin symmetry) is a symmetry which interchanges protons and neutrons, thus simultaneously interchanging up and down quarks, which implies the equivalence between the up (down) quark distribution in the proton and the down (up) quarks in the neutron. Currently, all fits to Parton Distribution Functions (PDFs) are preformed under the assumption of charge symmetry between neutrons and protons.

Boros et al. have proposed [1] that charge symmetry is broken such that the $d$ sea quark distribution in the nucleon is larger than the $u$ sea quark distribution for $x < 0.1$, which also results in a violation of flavor symmetry. Their paper notes that structure functions extracted in neutrino deep inelastic scattering experiments are dominated by the higher statistics data taken with neutrino (versus antineutrino) beams. They note that neutrino-induced charged current interactions couple to $d$ quarks and not to $u$ quarks, while the muon coupling to the $2/3$ charged $u$ quark is much larger than the coupling to the $1/3$ charge $d$ quark. Therefore, if the $d$ sea quark distribution is significantly larger than the $u$ sea quark distribution in the nucleon, there would be a significant difference between the nucleon structure functions as measured in neutrino and muon scattering experiments. However, both neutrino and muon scattering data have been taken on approximately isoscalar targets, such as iron or deuterium. Isoscalar targets have an equal number of neutrons and protons. A larger number of $d$ sea quarks than $u$ sea quarks in an isoscalar target implies a violation of charge symmetry. Therefore, Boros et al. proposed that a large charge symmetry violation of the sea quarks in the nucleon might explain the observed discrepancy ($10 \sim 15\%$) between neutrino and muon structure function data.

Boros et al. define the following charge symmetry violations in the nucleon sea.

$$\delta u(x) = \bar{u}(x) - \bar{d}(x),$$
$$\delta d(x) = \bar{d}(x) - \bar{u}(x),$$

where $\bar{u}(x)$ and $\bar{d}(x)$ are the distribution of the $u$ and $d$ sea anti-quarks in the proton, respectively. Similarly $\bar{u}(x)$ and $\bar{d}(x)$ are the distribution of the $u$ and $d$ sea anti-quarks in the neutron, respectively. The distributions for the quarks and antiquarks in the sea is assumed to be the same. The relations for CSV in the sea quark distributions are analogous to equations (1) and (2) for the sea anti-quarks. Charge symmetry in the valence quarks is assumed to be conserved, since there is good agreement between the neutrino and muon scattering data for $x > 0.1$.

Within this model, Boros et al. extract a large CSV from the difference in structure functions as measured in neutrino and muon scattering experiments. Theoretically, such a large charge symmetry violation (of order of 25% to 50%) is very unexpected. Therefore, the article has generated a significant amount of interest both within and outside the high energy physics community [4]. If the proposed model is valid, all parametrizations of PDFs would have to be modified. In addition, physics analyses which rely on the knowledge of PDFs (e.g. the extraction of the electro-weak mixing angle from the ratio of neutral current and charged current cross sections) would be significantly affected.

In this communication we show that the CSV models proposed by Boros et al. are ruled out by the $W$ charge asymmetry measurements made by the CDF experiment.
at the Fermilab Tevatron collider \cite{4}. These $W$ data provide a very strong constraint on the ratio of $d$ and $u$ quark momentum distributions in the proton over the $x$ range of 0.006 to 0.34.

Figure 1 shows the quantity $x\Delta(x) = x[\delta d(x) - \delta u(x)]/2$ required to explain the difference between neutrino and muon data, as given in Fig. 3 of Boros et al. \cite{5}. The average $Q^2$ of these data is about 4 (GeV/c)$^2$. The dashed line is the strange sea quark distribution [$x\delta s(x)$] in the nucleon as measured by the CCFR collaboration using dimuon events produced in neutrino nucleon interactions. Boros et al. state that the magnitude of implied charge symmetry violation is somewhere between the full magnitude of the strange sea and half the magnitude of the strange sea. Since the strange sea itself has been measured to be about half of the average of the $d$ and $u$ sea, this implies a charge symmetry violation of order 25% (at $x = 0.05$) and 50% (at $x = 0.01$).

However, as can be seen in Fig. 1, the shape of the strange sea does not provide a good parametrization of the charge symmetry violation, therefore, we have parametrized $x\Delta(x)$ (at $Q^2 = 4$ (GeV/c)$^2$ ) as follows. For $x > 0.1$, $x\Delta(x) = 0$. For $x < 0.01$, $x\Delta(x) = 0.15$, and for $0.01 < x < 0.1$, $x\Delta(x) = .15[\log(x) - \log(0.1)]/[\log(0.01) - \log(1)]$. This parametrization is shown as the solid line in Fig. 1. The dot-dashed line shows the value of our parametrization when evolved to $Q^2 = M^2_W$. Boros et al. suggest that it is theoretically expected that $\Delta(x) = \delta \bar{d}(x) = -\delta \bar{u}(x)$, which means that the sum of $u$ and $d$ sea distributions for protons and neutrons is the same. Within the assumption that $\Delta(x) = \delta \bar{d}(x) = -\delta \bar{u}(x)$, we use two models to parametrize the range of allowed changes in PDFs to introduce the proposed charge symmetry violations.

In Model 1, it is assumed that the standard PDF parametrizations are dominated by neutrino data and therefore represent the average of $d$ and $u$ sea quark distributions. Therefore, half of the CSV is introduced into the $u$ sea quark distribution and half of the effect is introduced into the $d$ sea quark distribution such that the average of $d$ and $u$ sea quark distributions is unchanged.

\begin{equation}
\pi^u(CSV) = \pi^u - \Delta(x)/2, \tag{3}
\end{equation}

\begin{equation}
\bar{d}^u(CSV) = \bar{d}^u + \Delta(x)/2, \tag{4}
\end{equation}

\begin{equation}
\pi^d(CSV) = \pi^d - \Delta(x)/2, \tag{5}
\end{equation}

\begin{equation}
\bar{d}^d(CSV) = \bar{d}^d + \Delta(x)/2. \tag{6}
\end{equation}

In Model 2, it is assumed that standard PDFs are dominated by muon scattering data, and therefore are good representation of the $2/3$ charge $u$ quark distribution. In this model, the entire effect is introduced into the $d$ sea quark distribution as follows;

\begin{equation}
\pi^u(CSV) = \pi^u, \tag{7}
\end{equation}

\begin{equation}
\bar{d}^u(CSV) = \bar{d}^u + \Delta(x), \tag{8}
\end{equation}

\begin{equation}
\pi^d(CSV) = \pi^d, \tag{9}
\end{equation}

\begin{equation}
\bar{d}^d(CSV) = \bar{d}^d + \Delta(x). \tag{10}
\end{equation}

Model 2 would change the total quark sea.

In order to have a precise test for the CSV effect, all PDFs have to be refitted based on the above two models. However, the ratio of $d$ and $u$ distribution will be almost the same whether we refit the PDFs or not. The $d/u$ ratio which has been extracted from $F_2^n/F_2^p$ measurements (assuming charge symmetry) is in fact the quantity $u^p/u^n$ which does not have any sensitivity to the proposed CSV effect. In order to test for CSV effects, measurements of $d^p/u^p$ or $d^n/u^n$ are required. Therefore, the CDF measurements of the $W$ charge asymmetry in $p\bar{p}$ collisions provide a unique test of CSV effects, because of the direct sensitivity of these data to the $d/u$ ratio in the proton (note that the $d$ and $u$ quark distributions at small $x$ are dominated by the quark-antiquark sea). We now proceed to show that these implementations of CSV in the nucleon sea are ruled out by the CDF $W$ charge asymmetry measurements at the Tevatron.

At Tevatron energies, $W^+ (W^-)$ bosons are produced in $p\bar{p}$ collisions primarily by the annihilation of $u$ ($d$) quarks in the proton and $\bar{d}$ ($\bar{u}$) quarks from the antiproton. Because $u$ quarks carry on average more momentum than $d$ quarks \cite{6}, the $W^+$ bosons tend to follow the direction of the incoming proton and the $W^-$ bosons' that of the antiproton. The charge asymmetry in the production of $W$ bosons as a function of rapidity ($y_W$) is therefore
related to the difference in the \(u\) and \(d\) quark distributions, and is roughly proportional \(d(x)/u(x)\), to the ratio of the difference and the sum of the quantities \(d(x)/u(x)\) (where \(x\) and \(x_2\) are the fractions of the proton momentum carried by the \(u\) and \(d\) quarks, respectively) (Note that the quark distributions in the proton are equal to the antiquark distributions in the antiproton). At large rapidity, \(x_1\) is larger than 0.1, which is a region where CSV does not exist. On the other hand \(x_2\) is in general less than 0.1 and a 25\% to 50\% CSV effect would imply a very large effect on the \(W\) asymmetry.

Since the \(W\) charge asymmetry is sensitive to the \(d/u\) ratio, it does not matter if the CSV effect at small \(x\) is present in either \(d\) or \(u\) sea quark. All of these models would result in a similar change in the \(W\) asymmetry.

Experimentally, the \(W\) rapidity is not determined because of the unknown longitudinal momentum of the neutrino from the \(W\) decay. What is actually measured by the CDF collaboration is the lepton charge asymmetry which is a convolution of the \(W\) production charge asymmetry and the well known asymmetry from the \(V\)-\(A\) \(W\) decay. The two asymmetries are in opposite directions and tend to cancel at large values of rapidity. However, since the \(V\)-\(A\) asymmetry is well understood, the lepton asymmetry is still sensitive to the parton distributions.

The lepton charge asymmetry is defined as:

\[
A(y_l) = \frac{d\sigma^+ / dy_l - d\sigma^- / dy_l}{d\sigma^+ / dy_l + d\sigma^- / dy_l},
\]

where \(d\sigma^+ (d\sigma^-)\) is the cross section for \(W^+ (W^-)\) decay leptons as a function of lepton rapidity, with positive rapidity being defined in the proton beam direction. The CDF data shown in Fig. 2 span the broad range of lepton rapidity (0.0 < \(|y_l| < 20\)) and provide information about the \(d/u\) ratio in the proton over the wide \(x\) range (0.066 < \(x < 0.34\)). Therefore, the CDF \(W\) asymmetry data would provide a strong tool to test the CSV models over a broad range of \(x\), and not just in part of the range as proposed in the Boros et al. model.

Also shown in Fig. 2 (solid line) are the predictions for the \(W\) asymmetry from QCD calculated to Next-to-Leading-Order (NLO) using the program DYRAD, with the CTEQ4M PDF parametrization for the \(d\) and \(u\) quark distributions in the proton (we have used CTEQ4 because it is the PDF set that has been used by Boros et al. in their paper). As pointed out by Yang and Bodek, the small difference between the data and the prediction of the CTEQ4M PDF at high rapidity is because the \(d\) quark distribution is somewhat underestimated at high \(x\) in the standard PDF parametrizations. The predictions of the CTEQ4M PDF with the proposed modifications by Yang and Bodek are shown as the dashed-dotted line in the figure.

The two dotted lines in Fig. 2 show the predicted \(W\) asymmetry for the CTEQ4M PDF with the proposed Boros et al. charge symmetry violation in the sea for Model 1 and Model 2, respectively. The CDF \(W\) data clearly rule out these models.

Most striking in this analysis is the broad range of lepton rapidity over which this disagreement occurs with the CSV models. This is suggestive that models of this class would be ruled out over a broad range of \(x\) and not just in part of the range proposed in the Boros et al. model.

In the direct measurement of the \(W\) mass at the Tevatron, the CDF \(W\) asymmetry data have been used to limit the error on \(M_W\) from PDFs to about 15 MeV. This has been done by calculating the deviation between the error weighted average measured asymmetry over the rapidity range of the data, and the predictions from various PDFs. This measured average asymmetry for the data is 0.087 ± 0.003. The predicted average asymmetries (weighted by the same errors as the data) are 0.094, 0.125, and 0.141 for the CTEQ4M PDF, and for Model 1 and Model 2, respectively. If we only accept PDFs which are within two standard deviations of the CTEQ4M PDF, the \(W\) asymmetry data rule out CSV effects at the level of more than 10 standard deviations for the two models with CSV effects.

Another precision measurement which is sensitive to CSV effects is the measurement of neutral-current scattering in neutrino-nucleon collisions. Just as the magnitude of the couplings to \(u\) and \(d\) quarks differ in
neutral-current $\mu$–$q$ scattering at NMC, the couplings to $u$ and $d$ quarks also differ in neutral-current $\nu$–$q$ scattering. In this case, the left-handed and right-handed couplings of the neutral current to quarks are given by $g_L = I_3 - Q\sin^2\theta_W$ and $g_R = -Q\sin^2\theta_W$, where $Q$ is the quark charge and $I_3$ is the third component of the weak isospin in the quark doublet, $+1/2$ for $u$-type quarks and $-1/2$ for $d$-type quarks. Therefore the CSV-inspired enhancement in the $d$ quark distributions will change the the cross-section for neutral-current scattering, even for an isoscalar target. Because these cross-section measurements are used to extract electroweak parameters, a CSV effect could then affect the precision measurements of $\sin^2\theta_W$.

The most precise measurements of neutral-current neutrino-quark scattering come from the CCFR [11] and NuTeV [12] experiments. As noted above, CCFR had a beam of mixed neutrinos and anti-neutrinos, dominated by neutrinos. The NuTeV experiment uses separate neutrino and anti-neutrino beams in its measurements to allow separation of neutral-current neutrino and anti-neutrino interactions. The NuTeV and CCFR experiments measure combinations of the ratios, $R^\nu$ and $R^\overline{\nu}$, (above a fixed hadron energy $\nu$ threshold of 20 GeV or 30 GeV in NuTeV and CCFR, respectively), where

$$R^\nu(\nu) \equiv \frac{\sigma^{\nu NC}_W}{\sigma^{\nu CC}_W} = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1 + r \pm 1) \sin^4\theta_W,$$

and $r \equiv \sigma^{CC}_W/\sigma^{CC}_W \sim 0.4$. The NuTeV experiment has extracted $\sin^2\theta_W$ using the combination $R^\nu - r R^\overline{\nu}$ which is insensitive to the effects of sea quarks, and thus not changed by CSV effects in sea, as in the Boros et al. model. However, the CCFR measurement with a mixed beam is equivalent to $R^\nu + 0.13 R^\overline{\nu}$ in which the sea quark contributions do not cancel.

Within the framework of Model 1, the modified PDFs leave the charged current neutrino data unchanged, but affect the level of the neutral current cross section. The effect of the Model 1 implementation of the Boros et al. model on the CCFR result has been calculated using the CTEQ4L PDF [5] in the cross-section model. The CCFR experiment extracts a $\sin^2\theta_W$ which is equivalent to $M_W = 80.35 \pm 0.21$ GeV [11], which can be compared to the current average of all direct $M_W$ measurements, 80.39 $\pm$ 0.06 GeV. Model 1 would increase the CCFR measured $M_W$ by 0.26 GeV. Since the CDF $W$ asymmetry data rule out a CSV effect at the the level of 1/5 of the magnitude of Model 1, the error from possible CSV effects in PDFs is less than 50 MeV. This illustrates the value of the CDF $W$ asymmetry data in limiting the systematic error from PDF uncertainties not only in the direct measurement of the $W$ mass in hadron colliders, but also in the indirect measurement of the $W$ mass in neutrino experiments.

In conclusion, the CDF $W$ asymmetry data rule out the Boros et al. model for charge symmetry violation in parton distributions [14] as the source of the difference between neutrino (CCFR) and muon (NMC) deep inelastic scattering data. Sources such as a possible difference in nuclear effects between neutrino and muon scattering, or a possible underestimate of the strange quark sea in the nucleon have been ruled out [1]. The experimental systematic errors between the two experiments, and improved theoretical analyses of massive charm production in both neutrino and muon scattering are both presently being investigated [13] as possible reasons for this discrepancy.

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[14] Boros et al. suggest that it is theoretically expected that $\Delta(x) = \delta^{u}(x) = -\delta^{d}(x)$, which means that the sum of $u$ and $d$ sea distributions for protons and neutrons is the same. The CDF W Asymmetry data indicate that the standard PDFs are correct for the proton and cannot be modified. However, if this relationship is relaxed, all the charge and flavor symmetry violation can be put into the PDFs for the neutron alone. Preserving $F^d_2$ one can propose the following relations:

$$\overline{\nu}(CSV) = \overline{\nu}^d; \overline{\nu}(CSV) = \overline{\nu}^u - 2\Delta(x)/5; \overline{\nu}(CSV) = \overline{\nu}^d - \overline{\nu}^u = 8\Delta(x)/5.$$

In this model, the total neutron sea is much larger than the proton sea, and there is a very large flavor symmetry violation only in the neutron.