Charge Symmetry Violating Contributions to Neutrino Reactions

J.T.Londergan

Department of Physics and Nuclear Theory Center,
Indiana University,
Bloomington, IN 47405, USA

A.W.Thomas

Department of Physics and Mathematical Physics,
and Special Research Center for the Subatomic Structure of Matter,
University of Adelaide, Adelaide 5005, Australia

(Dated: November 29, 2018)

Abstract

The NuTeV group has measured charged and neutral current reactions for neutrinos on iron targets. Ratios of these cross sections provide an independent measurement of the Weinberg angle. The NuTeV value for $\sin^2 \theta_W$ is three standard deviations larger than the value measured in other electroweak processes. By reviewing theoretical estimates of parton charge symmetry violation (CSV), we study CSV contributions to the NuTeV measurement. We conclude that charge symmetry violating effects should remove roughly 30% of the discrepancy between the NuTeV result and other determinations of $\sin^2 \theta_W$. 

*Electronic address: tlonderg@indiana.edu
†Electronic address: athomas@physics.adelaide.edu.au
I. INTRODUCTION

In recent years precise experiments have provided detailed information regarding the parton structure of the nucleon. One of the more striking developments was the measurement of significant differences between up and down antiquark distributions in the nucleon sea. The first clear evidence for this was obtained from muon DIS on deuterium by the NMC group [1, 2], that enabled a precise determination of the Gottfried Sum Rule [3]. Later this was more directly confirmed by Drell-Yan measurements in pp and pD reactions [4, 5, 6] and by semi-inclusive electroproduction at HERMES [7]. This sea quark flavor asymmetry, which had been anticipated [8] on the basis of spontaneously broken chiral symmetry [9], has been incorporated into the latest phenomenological parton distributions [10, 11].

Another approximate symmetry in parton distributions is charge symmetry, which involves rotation of 180° about the two axis in isospin space, and which corresponds to interchange of protons and neutrons (simultaneously interchanging up and down quarks). Our faith in the charge symmetry of parton distributions is justified from experience in nuclear physics, where this symmetry is respected to a high degree of precision [12, 13]. Until recently, the quantitative evidence which could be extracted from high energy experiments, although not particularly precise, was consistent with charge symmetric parton distributions [14]. As a result, all phenomenological analyses of deep inelastic scattering data in terms of parton distribution functions assume charge symmetry. Experimental verification of charge symmetry was difficult, first because high precision experiments were necessary to isolate charge symmetry violating (CSV) effects, second because the best tests required comparison of electromagnetic and neutrino-induced reactions, and third because CSV often mixes with quark flavor asymmetry effects.

Recent precise experiments have now significantly decreased the upper limits on parton CSV contributions. The NMC measurements of muon DIS on deuterium [1] provide values for the charged lepton structure function $F_2(x, Q^2)$. In a similar $Q^2$ regime the CCFR Collaboration [15] extracted the structure functions $F_2(x, Q^2)$ from neutrino–induced charge-changing reactions. In sec. II we review the comparison of these structure functions and we show that upper limits of a few percent can be placed on parton CSV in the region $0.01 \leq x \leq 0.4$. In sec. III we review theoretical models for charge symmetry violation and we present two models for CSV parton distribution and an estimate of CSV parton
distributions using phenomenological parton distributions.

Recently, the NuTeV experimental group has measured both neutral and charged-current cross sections for neutrinos and antineutrinos on iron targets [16]. As was originally pointed out by Paschos and Wolfenstein [17], ratios of these cross sections on isoscalar targets can provide an independent measurement of the Weinberg angle, \( \sin^2 \theta_W \). The value of \( \sin^2 \theta_W \) extracted by the NuTeV group is three standard deviations larger than the measured fit to other electroweak processes [18]. This striking result has led some people to suggest that they may be seeing evidence of physics beyond the Standard Model.

Because of the importance of this result, it is crucial that all the effects contributing to this result be estimated to the best of our abilities. The NuTeV group has recently published a paper [19] that estimates the contributions to their result from three sources: the excess of neutrons in their iron target; the possible contribution from strange quarks and the effects of parton charge symmetry violation. As we will discuss in the following section, the isoscalar correction (excess neutrons in iron) makes a rather large, but apparently well-determined, correction to the extracted value of the Weinberg angle. At present, even the sign of the contribution from strange quarks is uncertain. In this paper, we will show that we can predict the sign of the contribution from parton CSV with some confidence. We will demonstrate that different theoretical predictions of the magnitude of the CSV correction to the neutrino determination of the Weinberg angle are in reasonable agreement with each other. CSV contributions should decrease the discrepancy between this experiment and the value of the Weinberg angle extracted from electroweak experiments in the vicinity of the Z mass. This will be reviewed in Sec. IV.

II. EXTRACTION OF WEINBERG ANGLE FROM NEUTRINO SCATTERING

Paschos and Wolfenstein [17] showed that one could obtain an independent measurement of the Weinberg angle, by taking ratios of charged-current and neutral-current cross sections for neutrinos and antineutrinos on isoscalar targets. They proposed measuring the ratio

\[
R^- \equiv \frac{1}{\rho_0^2} \left( \frac{\langle \sigma^{\nu N_0}_{NC} \rangle - \langle \sigma^{\nu N_0}_{CC} \rangle}{\sigma^{\nu N_0}_{CC} - \langle \sigma^{\nu N_0}_{CC} \rangle} \right) = \frac{1}{2} - \sin^2 \theta_W
\]

In Eq. 1 \( \langle \sigma^{\nu N_0}_{NC} \rangle \) is the neutral-current inclusive cross section, integrated over \( x \) and \( y \), for neutrinos on an isoscalar target. The quantity \( \rho_0 \equiv M_W / (M_Z \cos \theta_W) \) is one in the Standard Model.
Model. Alternatively, Eq. \ref{eq:1} can be written as

\[
R^{-} = \frac{(R^{\nu} - R^{\bar{\nu}})}{1 - r R^{\nu}}, \quad r = \frac{\sigma^{\nu N_0}_{CC}}{\sigma^{\nu N_0}_{CC}}.
\]

\[
R^{\nu} = \frac{1}{\epsilon_{\nu}} \frac{\langle \sigma^{\nu N_0}_{NC} \rangle}{\langle \sigma^{\nu N_0}_{CC} \rangle}, \quad R^{\bar{\nu}} = \frac{1}{\epsilon_{\bar{\nu}}} \frac{\langle \sigma^{\bar{\nu} N_0}_{NC} \rangle}{\langle \sigma^{\bar{\nu} N_0}_{CC} \rangle}.
\tag{2}
\]

The NuTeV group used the Sign Selected Quadrupole Train beamline at FNAL to separate neutrinos and antineutrinos arising from pion and kaon decays following the interaction of 800 GeV protons. The resulting interaction events were observed in the NuTeV detector, and were required to deposit between 20 GeV and 180 GeV in the calorimeter. \textit{CC} and \textit{NC} events were distinguished by the event length in the counters, as \textit{CC} events contained a final muon that penetrated substantially farther than the hadron shower.

Rather than working directly with the Paschos-Wolfenstein ratio, the NuTeV collaboration measured the individual ratios \(R^{\nu}\) and \(R^{\bar{\nu}}\) defined in Eq. \ref{eq:2} and took the value of \(r\) from earlier experiments. From the result, \(R^{\nu} = 0.3916 \pm 0.0007\) and \(R^{\bar{\nu}} = 0.4050 \pm 0.0016\), they extracted \(\sin^2 \theta_W = 0.2277 \pm 0.0013\) (stat) \(\pm 0.0009\) (syst). This value is three standard deviations above the measured fit to other electroweak processes, \(\sin^2 \theta_W = 0.2227 \pm 0.00037\) \cite{18}. This result is striking, and if no other effects can account for this discrepancy, it may be evidence of physics beyond the Standard Model.

Several approximations have been made in deriving Eq. \ref{eq:1}. It is true only for isoscalar targets, includes only the contributions from light quarks, and assumes the validity of parton charge symmetry. The NuTeV group has recently investigated how their result changes when these assumptions are removed \cite{19}. The corrections to the Paschos-Wolfenstein ratio of Eq. \ref{eq:1} take the form

\[
\Delta R^{-} = \frac{S_{\nu}}{U_{\nu} + D_{\nu}} \left[ 2 \Delta_{d}^2 + 3 \left( \Delta_{u}^2 + \Delta_{d}^2 \right) \epsilon_c \right] + \frac{\left( 3 \Delta_{d}^2 + \Delta_{d}^3 \right)}{(U_{\nu} + D_{\nu})} \left[ -\delta N \left( U_{\nu} - D_{\nu} \right) + \frac{1}{2} \left( \delta U_{\nu} - \delta D_{\nu} \right) \right]
\]

\[
Q \equiv \int_{0}^{1} x q(x) \, dx
\]

\[
Q_{\nu} \equiv \bar{Q} - Q
\tag{3}
\]

In Eq. \ref{eq:3} the quantity \(Q\) is the total momentum carried by a quark of flavor \(q\), and the quantity \(Q_{\nu}\) is the total momentum carried by valence quarks of that flavor. \(\delta N = (N - Z)/A\) is the fractional neutron excess, \(\Delta_{u,d}^2 = (\epsilon_{L}^{u,d})^2 - (\epsilon_{R}^{u,d})^2\) and \(\epsilon_c\) is the kinematic suppression factor for massive charm production.
The isoscalar contribution (the term proportional to $\delta N$ in Eq. 3) is straightforward to calculate. Using the values $\delta N = 0.0567$, $3\Delta_u^2 + \Delta_d^2 = 0.4804$, and $(U_v - D_v)/(U_v + D_v) \sim 0.46$, gives an isoscalar correction to $\sin^2 \theta_W$ of about $-0.0125$. The NuTeV group reports an isoscalar correction of $-0.0080$, with a very small error [20]. This differs from the ‘naive’ correction of Eq. 3 because the NuTeV group corrects for factors like experimental cuts, experimental backgrounds and the enhanced sensitivity of their experiment to neutrino scattering at low $x$. All of these factors were used as input in a detailed Monte Carlo simulation of their experiment. However, Kulagin [21] has recently claimed that the uncertainties in the isoscalar corrections are likely to be considerably larger than estimated by the NuTeV group.

The contribution from strange quarks depends on the quantity $S_v \equiv S - \bar{S}$, the difference between the momentum carried by strange quarks and strange antiquarks. Even the sign of this quantity is not firmly established. Barone et al. [22] analyzed the CDHS neutrino charged-current inclusive cross sections and charged lepton structure functions [23], and argued that some improvement is obtained by allowing an asymmetric strange sea with $S_v > 0$. However, the CCFR [24] and NuTeV [25] charged-current and dimuon results show significant disagreement with the CDHS results at large $x$. The NuTeV group finds a best fit to their results with a slightly negative value $S_v = -0.0027 \pm 0.0013$.

In the remaining sections, we will review the origin of valence quark charge symmetry violation, and we will apply several theoretical models to estimate the CSV contribution to the NuTeV value for $\sin^2 \theta_W$.

III. VALENCE QUARK CHARGE SYMMETRY VIOLATION

Because the Paschos-Wolfenstein relation involves the difference between neutrino and antineutrino cross sections, it is dominated by contributions from valence parton distributions,

$$ q_v(x) = q(x) - \bar{q}(x) \ ,$$

for a particular quark flavor $q$. We can gain insight into the origin and magnitude of parton charge symmetry violation by using a method for calculating twist-two valence parton distributions developed by the Adelaide group [14, 26]. This method evaluates quark distributions
through the relation

\[ q(x, \mu^2) = M \sum_X |\langle X|\psi_+(0)|N\rangle|^2 \delta(M(1-x) - p_X^+) \]  

(5)

In Eq. 5, \( \psi_+ = (1 + \alpha_3)\psi/2 \) is the light front operator that removes a quark or adds an antiquark to the nucleon state \( |N\rangle \), \( \mu^2 \) represents the starting scale for the quark distribution, \( |X\rangle \) are all possible final states that can be reached with this operator, and \( p_X^+ \) is the plus component (\( p^+ \equiv p_3 + E(p) \)) of the residual system. Therefore, \( |X\rangle = 2q, 3q + 7, 4q + 27, \ldots \).

Thomas and collaborators showed that one could obtain quark distributions in semi-quantitative agreement with experiment using simple quark models such as the MIT bag [27] in Eq. 5, then evolving the resulting quark distribution from the bag scale \( \mu^2 \) to the final value of \( Q^2 \). The contribution to a quark distribution from intermediate state \( X \) produces a peak at a value \( x_p \sim 1 - M_X/M \), where \( M_X \) is the effective mass of the state \( X \). We note that for two-quark intermediate states, \( x_p \sim 1/3 \), while \( x_p \) is negative for states with four or more quarks. Consequently, for \( x \geq 0.2 \), where valence quarks dominate, qualitative estimates can be obtained by including only two-quark intermediate states in Eq. 5. Most importantly, this observation means that the major qualitative features of the spin and flavor dependence of the valence parton distribution functions can be understood simply in terms of the hyperfine mass splitting between two-quark states with spin zero or one [26, 28]. A similar analysis can also explain the spin and flavor dependence of strange baryon parton distributions at large \( x \) [29], and also quark fragmentation functions at large energy fraction \( z \) [30].

We can use Eq. 5 to estimate charge symmetry violating effects, e.g., the difference between the up quark valence distribution in the proton and the down quark in the neutron, \( \delta d_v(x) = d^p_v(x) - u^n_v(x) \). There are four sources of CSV contributions: charge symmetry violation in the quark wavefunctions; electromagnetic effects that break charge symmetry; mass differences of the struck quark; and mass differences in the spectator multi-quark systems. Model quark wavefunctions are found to be almost invariant under the small mass changes typical of CSV. At sufficiently high energies, electromagnetic effects should also be small, and these are neglected. Consequently, parton charge symmetry violation will arise predominantly through mass differences \( m_d - m_u \) of the struck quark, and from mass differences in the spectator multi-quark system. Both of these contributions will result in small shifts in the argument of the energy-conserving delta function in Eq. 5. Since at large \( x \) the
contribution to the parton distribution is dominated by the two-quark intermediate state, we can thus obtain quantitative estimates of the sign and magnitude of parton CSV from these terms. We stress that the change in the mass of the spectator pair is exactly the same mechanism that leads (through a much larger mass difference) to an understanding of the major features of the spin and flavor dependence of valence distributions, therefore one has a fair degree of confidence in this particular term.

Consider the “minority valence quark” CSV term,

$$\delta d_v(x) = d_p^v(x) - u_n^v(x) .$$

The main contribution to minority valence quark CSV arises from the mass of the diquark system, which is $uu$ for the proton and $dd$ for the neutron. The two-quark contribution to the valence quark distribution will peak at $x_p^p \sim 1 - M_{uu}/M$ for $d_p^v$ and $x_p^n \sim 1 - M_{dd}/M$ for $u_n^v$, thus the down quark distribution in the proton will be shifted to higher $x$ and the up quark distribution in the neutron will be shifted to lower $x$. This means that, at large $x$, $\delta d_v(x)$ will be positive.

Next, we consider the “majority valence quark” CSV term,

$$\delta u_v(x) = u_p^v(x) - d_n^v(x) .$$

The mass of the diquark state is $ud$ for both $u_p^v$ and $d_n^v$. As a result, the two-quark contribution to the majority quark valence distribution will peak at $x_p^p \sim 1 - M_{ud}/M^p$ for $u_p^v$ and $x_p^n \sim 1 - M_{ud}/M^n$ for $d_n^v$. As a result we expect $\delta u_v(x)$ to be negative at large $x$.

An important constraint on CSV parton distributions is that they respect the normalization of valence quarks. The integral over $x$ of valence quark distributions must give the total number of valence quarks, i.e.,

$$\int_0^1 u_p^v(x) \, dx = \int_0^1 d_n^v(x) \, dx = 2 ,$$

$$\int_0^1 d_p^v(x) \, dx = \int_0^1 u_n^v(x) \, dx = 1 ,$$

and hence Eq. (8) requires that

$$\int_0^1 \delta d_v(x) \, dx = \int_0^1 \delta u_v(x) \, dx = 0 .$$

It is important that valence quark CSV distributions obey this constraint, otherwise one is effectively changing the total number of up or down valence quarks in the nucleon.
FIG. 1: Valence quark CSV contributions, $x\delta q_v(x)$ vs. $x$. Solid line: $x\delta u_v$; dash-dot line: $x\delta d_v$. Calculated using MIT bag model wavefunctions by Rodionov et al., Ref. [31], and evolved to $Q^2 = 10$ GeV$^2$.

Since we can infer the sign and relative magnitude of the CSV parton distributions at large $x$, and these distributions must integrate to zero, we can obtain at least qualitative values for the valence CSV distributions. $\delta d_v(x)$ will be positive at large $x$ and thus negative at small $x$, while $\delta u_v(x)$ will be negative at large $x$ and positive at small $x$. In Fig. 1 we show $x\delta q_v(x)$ for valence up and down distributions as calculated by Rodionov, Thomas and Londergan [31]. These distributions are calculated from Eq. 5 using an MIT bag model for the quark wavefunctions. These numerical calculations included all four sources of CSV noted earlier. The resulting CSV distributions were evaluated at the bag scale and evolved upwards in $Q^2$. The distributions shown in Fig. 1 are evolved to $Q^2 = 10$ GeV$^2$. The parton distributions exhibit the qualitative effects that we inferred; at large $x$, $\delta d_v(x) > 0$ and $\delta u_v(x) < 0$. The CSV distributions must change sign at small $x$ to satisfy the requirement of valence quark conservation, summarized in Eq. 9.

Charge symmetry violating parton distributions were also calculated by Sather [32]. Starting also from Eq. 5 Sather derived the following analytic approximation relating CSV
distributions to valence parton distributions,

\[
\delta d_v(x) = -\frac{\delta M}{M} \frac{d}{dx} [xd_v(x)] - \frac{\delta m}{M} \frac{d}{dx} d_v(x)
\]

\[
\delta u_v(x) = \frac{\delta M}{M} \left( -\frac{d}{dx} [xu_v(x)] + \frac{d}{dx} u_v(x) \right)
\]  (10)

In Eq. 10 \(\delta M = M_n - M_p = 1.3\) MeV is the neutron-proton mass difference, \(\delta m = m_d - m_u\) is the down-up quark mass difference, and \(M\) is the average nucleon mass. To calculate the CSV parton distributions, Sather used parton distributions obtained from the MIT bag model in Eq. 10. Qualitatively, Sather’s CSV parton distributions are quite similar to those of Rodionov et al. However, \(\delta u_v(x)\) is smaller than the corresponding quantity for Rodionov et al., and Sather’s CSV distributions peak at somewhat smaller \(x\). Sather’s CSV distributions are qualitatively similar to those shown in Fig. 2.

Both of these charge symmetry violating distributions were constructed using bag model wavefunctions. Such wavefunctions can give qualitative agreement with phenomenological parton distributions, but these model-generated parton distributions systematically underpredict the results of phenomenological distributions at large \(x\). Here, we present a method for generating valence quark CSV parton distributions from phenomenological distributions. We will use the approximate formula derived by Sather \[32\], Eq. 10 that relates CSV parton distributions to the derivatives of valence quark parton distributions.

Although Sather obtained his CSV distributions by using parton distributions from the MIT bag model in Eq. 10, we will insert phenomenological parton distributions into this equation. There is a problem with this approach. As we pointed out in Eq. 9, conservation of valence quark probability requires that the integral over all \(x\) of \(\delta q_v\) in Eq. 10 be zero. Since the terms in this equation are just derivatives of parton distributions, integration over \(x\) simply involves evaluating the parton distributions at zero and one. However, phenomenological parton distributions go like \(x^{-1/2}\) in the limit \(x \to 0\), hence when phenomenological distributions are used the integral of the CSV distributions in Eq. 10 will not be zero, in fact the integrals will blow up.

The problem originates because Eq. 10 is a reasonable approximation for the parton distribution that arises when a nucleon consisting of three valence quarks splits into a quark and diquark. This gives the dominant contribution to the parton distribution at large \(x\). However, at small \(x\) the valence distribution is dominated by higher mass Fock states that include many quark-antiquark pairs. For states involving such large excitations, the effects
TABLE I: Parameters for valence quark distribution from CTEQ4LQ parton distribution, Ref. [35].

|        | N   | α        | β        | C      | γ  |
|--------|-----|----------|----------|--------|----|
| $u_v$  | 1.315 | -0.427   | 3.281    | 10.614 | 0.607 |
| $d_v$  | 0.852 | -0.427   | 4.060    | 4.852  | 0.266 |

of quark and nucleon mass differences should be negligible. However, Eq. 10 incorrectly predicts very large contributions at small $x$. Consequently, we need to suppress the large CSV effects produced by Eq. 10 at small $x$. We will deal with this problem in a simple, and completely phenomenological, way. Parton distributions from the CTEQ collaboration [34, 35] have been parameterized using the form

$$q_v(x) = N [x^\alpha + C x^\gamma] (1 - x)^\beta$$

The small-$x$ behavior is governed by the parameter $\alpha \sim -0.5$. We want a modified parton distribution that will vanish at small $x$, leaving the large-$x$ behavior relatively unchanged. We thus replace the CTEQ parton distributions $q_v(x)$ in Eq. 10 with $\tilde{q}_v(x)$, defined by

$$\tilde{q}_v(x) = N [x^\alpha + C x^\gamma] \left[ (1 - x)^\beta - (1 - x)^{\beta + 12} \right]$$

By inspection, $\tilde{q}_v(x)$ vanishes at $x = 0$, and for large $x$ there is a very small difference between the modified parton distribution of Eq. 12 and the phenomenological parton distribution.

We calculated valence quark CSV distributions using Eq. 10 with the CTEQ4LQ phenomenological parton distributions [35], modified using Eq. 12. The coefficients for the CTEQ4LQ parton distributions, appropriate for $Q^2 = 0.49$ GeV$^2$, are given in Table I.

Sather’s analytic expression, Eq. 10, is appropriate for a nucleon at a low starting scale, of order $Q^2 \sim 0.25 - 0.5$ GeV$^2$. The CTEQ4LQ parton distribution [35] was introduced specifically for starting scale $Q^2 = 0.49$ GeV$^2$. The resulting CSV distributions were evolved to the higher value $Q^2 = 20$ GeV$^2$ appropriate for the NuTeV experiment, using the QCD evolution program of Miyama and Kumano [36]. The evolved CSV parton distributions are shown in Fig. 2. The solid curve shows $x\delta d_v$ and the dash-dotted curve gives $x\delta u_v$. 
FIG. 2: Valence quark CSV contributions, $x\delta q_v(x)$ vs. $x$. Solid line: $x\delta d_v$; dash-dotted line: $x\delta u_v$. Calculated from valence quark distributions using the analytic approximation of Sather, Ref. [32], and the CTEQ4LQ parton distributions of Ref. [34], modified according to Eq. 12. These distributions were then evolved from the starting scale $Q^2 = 0.49$ GeV$^2$ to $Q^2 = 20$ GeV$^2$ appropriate for the NuTeV experiment.

IV. CHARGE SYMMETRY VIOLATING CONTRIBUTIONS TO NEUTRINO REACTIONS

Using the valence quark CSV distributions reviewed in Sec. III, we can estimate the CSV contribution to the extracted value of $\sin^2 \theta_W$. From Eq. 3, the CSV corrections to the Paschos-Wolfenstein ratio are of the form

$$\Delta R_{\text{CSV}}^- = \left(3\Delta_u^2 + \Delta_d^2\right) \frac{\delta U_v - \delta D_v}{2(U_v + D_v)} = \Delta U_v + \Delta D_v$$

$$Q_v = \int_0^1 x q_v(x) \, dx$$

$$\delta D_v = \int_0^1 x \left[d_v^p(x) - u_v^n(x)\right] \, dx$$

$$\delta U_v = \int_0^1 x \left[u_v^p(x) - d_v^n(x)\right] \, dx$$

(13)

In Table II we show the contributions of the different theoretical CSV estimates to the Paschos-Wolfenstein ratio. We have broken down the individual contributions so that $\Delta U_v$ and $\Delta D_v$ are the total CSV effects arising from $\delta U_v$ and $\delta D_v$, respectively. From Fig. 1 in all cases both $\delta U_v$ and $\delta D_v$ make a negative contribution. Therefore the net CSV contribution will be negative. This will decrease the discrepancy between the value of $\sin^2 \theta_W$ extracted in the NuTeV experiment, and the best value obtained from high-energy electroweak interactions.
TABLE II: CSV corrections to determination of $\sin^2 \theta_W$ in neutrino scattering. $PW$ is contribution to the Paschos-Wolfenstein ratio, $Nu$ is weighted by the NuTeV functional. $\Delta U$ ($\Delta D$) is total contribution from $\delta u_v$ ($\delta d_v$), and $Tot$ is total CSV correction.

|       | $\Delta U_{PW}$ | $\Delta D_{PW}$ | $Tot_{PW}$ | $\Delta U_{Nu}$ | $\Delta D_{Nu}$ | $Tot_{Nu}$ |
|-------|------------------|------------------|------------|------------------|------------------|------------|
| Rodionov | -.0010           | -.0011           | -.0020     | -.00065          | -.00081          | -.0015     |
| Sather  | -.00078          | -.0013           | -.0021     | -.00060          | -.0011           | -.0017     |
| analytic| -.00075          | -.0013           | -.0021     | -.0005           | -.0009           | -.0014     |

Table II shows that CSV contributions to the Paschos-Wolfenstein ratio from three theoretical models give almost identical results, $-0.0020$ or $-0.0021$. Since the value of $\sin^2 \theta_W$ from the NuTeV experiment, without CSV corrections, was 0.005 larger than the best value from electromagnetic interactions, our calculated CSV effect would reduce the discrepancy between the neutrino and electromagnetic measurements of $\sin^2 \theta_W$ by 40%.

However, as pointed out by the NuTeV group [19], it is not appropriate to use Eq. 13 to determine the CSV effects on the value of $\sin^2 \theta_W$, as the NuTeV extraction of this quantity does not rely on the Paschos-Wolfenstein ratio, but instead uses the absolute ratios $R^v$ and $R^\nu$ defined in Eq. 2 and compares the results with a full Monte Carlo simulation of the experimental processes. The NuTeV group produced functionals that give the sensitivity of their observables to various effects. These are summarized in a single integral,

$$\Delta \mathcal{E} = \int_0^1 F[\mathcal{E}, \delta; x] \delta(x) \, dx$$

Eq. 14 gives the change in the extracted quantity $\mathcal{E}$ resulting from the symmetry violating quantity $\delta(x)$. The functionals appropriate for the observable $\sin^2 \theta_W$ and the parton CSV distributions, were provided in Ref. [19].

We have taken the parton CSV distributions and folded them with the NuTeV functionals. The net CSV correction to the value of $\sin^2 \theta_W$ is listed as $Tot_{Nu}$ in Table II. The CSV contributions are still negative, i.e., they decrease the discrepancy between the neutrino and electromagnetic measurements of the Weinberg angle. However, the CSV change in $\sin^2 \theta_W$ is slightly smaller than estimated in Eq. 13. This is because the NuTeV experiment is somewhat more sensitive to small-$x$ physics than to effects at larger $x$. The CSV parton distributions, weighted by $x$, change sign at small $x$ and reach a maximum at larger $x$. 
Thus the functionals, which emphasize the CSV distributions at small $x$ where they are small and change sign, and de-emphasize them at larger $x$, give a smaller CSV effect than predicted by the Paschos-Wolfenstein ratio. Nevertheless, the CSV contributions to the NuTeV result, weighted with their functionals, range from $-0.0014$ to $-0.0017$, and thus reduce the discrepancy between the neutrino and electromagnetic measurements of $\sin^2 \theta_W$ by roughly 30%.

The NuTeV group estimated the CSV correction [19] and obtained a much smaller value than ours. However, in order to obtain CSV parton distributions, they took the ratio $\delta q_v(x)/q_v(x)$ from Rodionov et al. [31], and multiplied this ratio by parton distributions determined from neutrino scattering. Since the ratio was determined using parton distributions from a quark model, and the parton distributions were obtained from quite a different source, we are not convinced of the accuracy of the resulting CSV distributions. In particular, CSV distributions constructed in this way will not satisfy any relation such as Eq. [10] nor will they satisfy valence quark conservation of Eq. [9].

V. CONCLUSIONS

We have reviewed the corrections that parton charge symmetry violation should make in determining $\sin^2 \theta_W$ in neutrino scattering. Although parton CSV effects are sufficiently small that neither their sign nor magnitude has been measured to date, we argued that at large $x$ the CSV distribution $\delta d_v(x)$ should be positive and $\delta u_v(x)$ should be negative. The CSV distributions must preserve the overall number of valence quarks in the neutron, hence from Eq. [9] both CSV distributions must change sign at small $x$.

We investigated two theoretical models of parton CSV. In both cases, the parton distributions are calculated from a model of QCD, such as the MIT bag, and the models determined how the CSV distributions could be related to the parton distributions and their derivatives. In a third case, we inserted phenomenological parton distributions from the CTEQ group into analytic expressions relating the CSV distributions to parton distributions. We removed the tendency of these analytic expressions to (incorrectly) give too much weight to the small-$x$ region, by damping the phenomenological distributions at very small $x$. In all cases, the CSV distribution was obtained at a low starting scale, and then evolved to higher $Q^2$, more appropriate for the $Q^2$ value of the neutrino experiments.
All of these theoretical CSV distributions serve to decrease the value of $\sin^2 \theta_W$ extracted from the NuTeV experiment; the size of these corrections was remarkably similar, ranging from $-0.0014$ to $-0.0017$. Since the value of $\sin^2 \theta_W$ extracted from neutrino scattering was greater than that obtained from electromagnetic interactions by $+0.005$, inclusion of a charge symmetry violating contribution of this magnitude would reduce this discrepancy by about 30%. We emphasize that CSV effects have yet to be confirmed by direct experiment, so our calculations only give the best theoretical estimate of these contributions. The predicted CSV effects arise from the same mechanism that correctly predicts the spin and flavor dependence of valence quark distributions, so we would be surprised if our CSV effects did not have the correct sign and roughly the right magnitude. It is rather remarkable that although the predicted corrections from parton charge symmetry violation are quite small, high energy experiments have now reached a precision where even small absolute effects have a significant impact on our ability to extract fundamental quantities.

Acknowledgments

This work was supported in part by the Australian Research Council. One of the authors [JTL] was supported in part by the National Science Foundation research contract PHY–0070368. The authors wish to thank G.P. Zeller and K. McFarland of the NuTeV collaboration for very useful comments regarding the NuTeV measurements and calculations, and about CSV contributions to extraction of the Weinberg angle. JTL wishes to acknowledge discussions with W. Melnitchouk and C. Benesh.

References

[1] NMC-Collaboration, M. Arneodo et al., Nucl. Phys. B483, 3 (1997).
[2] NMC-Collaboration, P. Amaudruz et al., Phys. Rev. Lett. 66, 2712 (1991); Phys. Lett. B295, 159 (1992).
[3] K. Gottfried, Phys. Rev. Lett. 18, 1174 (1967).
[4] NA51-Collaboration, A. Baldit et al., Phys. Lett. B332, 244 (1994).
[5] E866-Collaboration, E. A. Hawker et al., Phys. Rev. Lett. 80, 3715 (1998).
[6] E866-Collaboration, R.S. Towell et al., Phys. Rev. D64, 052002 (2001).
[7] HERMES Collaboration, K. Ackerstaff et al., Phys. Rev. Lett. 81, 5519 (1998).
[8] A. W. Thomas, Breaking In The Sea,” Phys. Lett. B 126, 97 (1983).
[9] A. W. Thomas, W. Melnitchouk and F. M. Steffens, Phys. Rev. Lett. 85, 2892 (2000).
[10] CTEQ Collaboration, H. L. Lai et al., Eur. Phys. J. C12, 375 (2000).
[11] MRST Collaboration, A.D. Martin et al., Eur. Phys. J. C4, 463 (1998).
[12] G. A. Miller, B. M. K. Nefkens and I. Slaus, Phys. Rep. 194, 1 (1990).
[13] E. M. Henley and G. A. Miller in Mesons in Nuclei, eds M. Rho and D. H. Wilkinson (North-Holland, Amsterdam 1979).
[14] J. T. Londergan and A. W. Thomas, in Progress in Particle and Nuclear Physics, Volume 41, p. 49, ed. A. Faessler (Elsevier Science, Amsterdam, 1998).
[15] CCFR-Collaboration, W. G. Seligman et al., Phys. Rev. Lett. 79, 1213 (1997).
[16] NuTeV Collaboration, G.P. Zeller et al., Phys. Rev. Lett. 88, 091802 (2002).
[17] E. A. Paschos and L. Wolfenstein, Phys. Rev. D7, 91, (1973).
[18] D. Abbaneo et al., hep-ex/0112021, unpublished.
[19] NuTeV Collaboration, G.P. Zeller et al., Phys. Rev. D65, 111103 (2002).
[20] G.P. Zeller, private communication.
[21] S.A. Kulagin, hep-ph/0301045, unpublished.
[22] V. Barone et al., Eur. Phys. J. C12, 243 (2000).
[23] CDHS Collaboration, P. Berge et al., Z. Phys. C49, 607 (1991).
[24] CCFR Collaboration, U.K. Yang et al., Phys. Rev. Lett. 86, 2742 (2001).
[25] NuTeV Collaboration, M. Goncharov et al., Phys. Rev. D64, 112006 (2001).
[26] A. I. Signal and A. W. Thomas, Phys. Lett. B191, 205 (1987); A. W. Schreiber, A. W. Thomas and J. T. Londergan, Phys. Rev. D 42, 2226 (1990).
[27] A. Chodos et al., Phys. Rev. D9, 3471 (1974).
[28] F.E. Close and A. W. Thomas, Phys. Lett. B212, 227 (1988).
[29] C. Boros, J. T. Londergan and A.W. Thomas, Phys. Rev. D61, 014007 (2000).
[30] C. Boros, J. T. Londergan and A.W. Thomas, Phys. Rev. D62, 014021 (2000).
[31] E. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A9, 1799 (1994).
[32] E. Sather, Phys. Lett. B274, 433 (1992).
[33] C. J. Benesh and T. Goldman, Phys. Rev. C55, 441 (1997).
[34] CTEQ Collaboration, H. L. Lai et al., Phys. Rev. D51, 4763 (1995).
[35] CTEQ Collaboration, H. L. Lai et al., Phys. Rev. D55, 1280 (1997).
[36] M. Miyama and S. Kumano, Comp. Phys. Comm. 94, 185 (1996).