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Current status of parton charge symmetry

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Abstract. We review constraints on parton charge symmetry from various experiments. Recently charge symmetry violation (CSV) has been included in a global fit to high energy data. We show that CSV compatible with all high energy data would be able to remove completely the NuTeV anomaly.

PACS. 11.30.Hv Flavor Symmetries – 13.15.+g Neutrino Interactions – 13.60.Hb Total and inclusive cross-sections, including deep inelastic structure functions

1 Experimental limits on parton CSV

Charge symmetry is a restricted form of isospin invariance involving a rotation of 180° about the "2" axis in isospin space. For parton distributions, charge symmetry involves interchanging up and down quarks while simultaneously interchanging protons and neutrons. In nuclear physics, charge symmetry is generally obeyed at the level of a fraction of a percent [1,2]. Charge symmetry violation (CSV) in parton distribution functions (PDFs) arises from two sources; from the difference $\delta m \equiv m_d - m_u$ between down and up current quark masses, and from electromagnetic (EM) effects. Since charge symmetry is so well satisfied at lower energies, it is natural to assume that it holds for parton distributions. At present, there is no direct experimental evidence of substantial violation of charge symmetry in parton distribution functions (PDFs).

In a recent paper [3], we have reviewed experimental and theoretical estimates for parton CSV, and have discussed potential corrections to the extraction of the Weinberg angle in neutrino deep inelastic scattering (DIS). We summarize our arguments here. The most stringent upper limits on parton CSV come from comparing the structure function $\overline{F_2}^W$, the average of ν and $\bar{\nu}$ charged current reactions, and the structure function F_2^γ for charged lepton DIS, on isoscalar targets (N_0). In leading order (LO), F_2^γ depends on the squared charges of the quarks, while F_2^W depends on the quark weak charges. Assuming charge symmetry gives a simple relation between the structure functions, defined as the "charge ratio" $R_c(x, Q^2)$. To lowest order in the (presumably small) CSV terms

$$R_c(x) \equiv \frac{F_2^{\gamma N_0}(x) + x\left(s(x) + \bar{s}(x) - c(x) - \bar{c}(x)\right)/6}{5\overline{F_2}^{WN_0}(x)/18}$$
$$\approx 1 + \frac{3x\left(\delta u(x) + \delta\bar{u}(x) - \delta d(x) - \delta\bar{d}(x)\right)}{10\,Q(x)}$$

$$Q(x) = \sum_{j=[u,d,s,c]} x\left[q_j(x) + \bar{q}_j(x)\right] \qquad (1)$$

1 introduces the CSV parton distributions,

$$\delta u(x) = u^p(x) - d^n(x); \quad \delta d(x) = d^p(x) - u^n(x), \qquad (2)$$

with analogous relations for antiquarks. Deviation of $R_c(x)$ from unity would indicate a CSV contribution.

The most precise neutrino measurements were obtained by the CCFR group [4], who extracted the F_2 structure function for ν-Fe and $\bar{\nu}$-Fe reactions. Muon DIS measurements were obtained by the NMC group [5,6], who measured F_2 structure functions for muon interactions on deuterium at muon energies $E_\mu = 90$ and 280 GeV. Taking into account many corrections (relative normalizations; heavy quark threshold effects; nuclear effects; corrections for excess neutrons in iron; contributions from s and c quarks), CCFR obtained results consistent with unity at about the $2-3\%$ level, in the range $0.1 \leq x \leq 0.4$. From (1), this gives an upper limit to parton CSV effects in the $6-9\%$ range. At smaller x, R_c appeared to deviate significantly from unity. However, upon re-analysis [7] the ratio agrees with unity at the $2-3\%$ level down to $x \sim 0.03$, as significant effects were found from NLO treatment of charm mass corrections, and separation of the F_2 and F_3 structure functions in ν DIS.

Other limits on parton CSV can come from measurements of $W^\pm$ asymmetry in a $p-\bar{p}$ collider. Since u quarks carry more momentum than d quarks, the direction of the W^+ and p tend to be aligned, as do the W^- and $\bar{p}$. Measurement of the W charge asymmetry is thus quite sensitive to the proton's u and d distributions. Conversely, charged lepton DIS on an isoscalar target tends to be more sensitive to u^n than to d^p, as it is more heavily weighted due to the squared quark charge. Comparison of, say, the CDF W charge asymmetry [8] and NMC $\mu - D$ DIS can constrain some aspects of parton CSV.

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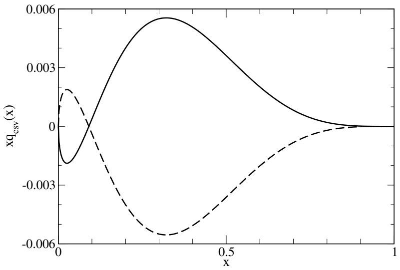

Fig. 1. The valence quark CSV function from [9], corresponding to best fit value $\kappa = -0.2$ defined in 3. *Solid curve*: $x\delta d_{\mathrm{v}}(x)$; *dashed curve*: $x\delta u_{\mathrm{v}}(x)$

2 Phenomenology and theory of parton CSV

Because CSV effects are typically very small at nuclear physics energy scales, all previous phenomenological PDFs have assumed the validity of parton charge symmetry. However, Martin, Roberts, Stirling and Thorne (MRST) [9] have recently studied the uncertainties in parton distributions arising from a number of factors, including isospin violation. MRST chose a specific model for valence quark charge symmetry violating PDFs:

$$\delta u_{\mathrm{v}}(x) = -\delta d_{\mathrm{v}}(x) = \kappa(1-x)^4 x^{-0.5}(x-.0909). \tag{3}$$

At both small and large x the MRST CSV PDFs have the same form as the valence distributions. The first moment of the MRST valence CSV function is zero; this must be the case since, *e.g.,* the integral $\langle \delta u_{\mathrm{v}} \rangle$ is just the total number of valence up quarks in the proton minus the number of down quarks in the neutron. The second moment of this function represents the CSV momentum asymmetry; $\delta U_{\mathrm{v}} \equiv \langle x\delta u_{\mathrm{v}}(x) \rangle$ is the difference in total momentum carried by u^p_{v} and d^n_{v}. The MRST valence CSV distributions require that δu_{v} and δd_{v} have opposite signs at large x, in agreement with theoretical predictions. This condition also insures that valence quarks in the proton and neutron carry an equal amount of total momentum (this is strictly true only at the starting scale, since the momentum asymmetry is not constant under QCD evolution; however MRST find that it does not change very much over a fairly wide Q^2 range). The overall coefficient κ was varied in a global fit to a wide range of high energy data.

The value $\kappa = -0.2$ minimised χ^2. Their χ^2 had a shallow minimum with the 90% confidence level obtained for the range $-0.8 \le \kappa \le +0.65$. In Fig. 1 we plot the valence quark CSV PDFs corresponding to the MRST best fit value $\kappa = -0.2$. Within the 90% confidence region for the global fit, the valence quark CSV PDFs could be either four times as large as in Fig. 1, or it could be three times as big with the opposite sign. CSV distributions with this shape, and for κ within this range, will not disagree seriously with any of the high energy data used to extract quark and gluon PDFs.

The MRST group also searched for CSV in the sea quark sector. Again, they chose a specific form for sea quark CSV, dependent on a single parameter, *i.e.,*

$$\bar{u}^n(x) = \bar{d}^p(x)\,[1+\delta]$$

$$\bar{d}^n(x) = \bar{u}^p(x)\,[1-\delta] \tag{4}$$

Somewhat surprisingly, evidence for sea quark CSV in the global fit was substantially stronger than for valence quark CSV. The best fit was obtained for $\delta = 0.08$, corresponding to an 8% violation of charge symmetry in the nucleon sea. This is considerably larger than theoretical estimates of sea quark CSV [10]. The χ^2 for this value is substantially better than with no CSV, primarily because of improvement in fits to the NMC $\mu - D$ DIS data [5,6] and to the E605 Drell-Yan data [11], when sea quark CSV is included. The MRST best-fit values will necessarily give reasonable agreement with the charge ratio of (1), since both the CCFR ν X-sections and NMC muon DIS are included in the global fit. The MRST group also includes the CDF W charge asymmetry measurements [8], so that the MRST global fit PDFs including CSV are compatible with all data sets that are most sensitive to charge symmetry violating effects.

The MRST phenomenological CSV distributions agree rather well with two earlier predictions using quark models. The Adelaide group [12] developed a method for calculating twist-two valence PDFs from quark model wavefunctions. Unlike earlier calculations, this model guaranteed correct support for the PDFs. Rodionov et al. [13] extended this model to calculate valence quark CSV. Sather [14] approximated the dependence of valence quark PDFs on the quark and nucleon masses, and obtained analytic approximations relating valence quark CSV to derivatives of the valence PDFs. Although there are several differences between the models of Sather and Rodionov, their predictions of valence quark CSV are quite similar. In Fig. 2, we show the theoretical valence quark CSV prediction of Rodionov. The solid curve is $x\delta u_{\mathrm{v}}(x)$, while the dot-dashed curve is $x\delta d_{\mathrm{v}}(x)$, both evolved to $Q^2 = 10$ GeV^2. Qualitatively, the results of Rodionov *et al.* are very similar to the best-fit phenomenological CSV distribution of MRST, shown in Fig. 1. The sign and relative magnitude of both $\delta d_{\mathrm{v}}(x)$ and $\delta u_{\mathrm{v}}(x)$ are quite similar in both phenomenology and theory. The second moments of the CSV PDFs (which give the total momentum asymmetry between, *e.g.,* u^p_{v} and d^n_{v}) of the MRST and Rodionov distributions are equal to within 10%.

3 Parton CSV and the NuTeV anomaly

In 1973, Paschos and Wolfenstein [15] suggested that the ratio of neutral-current (NC) and charge-changing (CC) neutrino cross sections on isoscalar targets could provide an independent measurement of the Weinberg angle ($\sin^2\theta_W$). The Paschos-Wolfenstein (PW) ratio R^- is given by

$$R^- \equiv \frac{\langle \sigma_{NC}^{\nu N_0} \rangle - \langle \sigma_{NC}^{\overline{\nu} N_0} \rangle}{\rho_0^2 \left(\langle \sigma_{CC}^{\nu N_0} \rangle - \langle \sigma_{CC}^{\overline{\nu} N_0} \rangle \right)} = \frac{1}{2} - \sin^2\theta_W = \frac{R^\nu - R^{\overline{\nu}}}{1 - r\,R^\nu}. \tag{5}$$

In 5, $\langle \sigma_{NC}^{\nu N_0} \rangle$ is the NC inclusive total cross section for neutrinos on an isoscalar target. The quantity ρ_0 is one in the Standard Model.

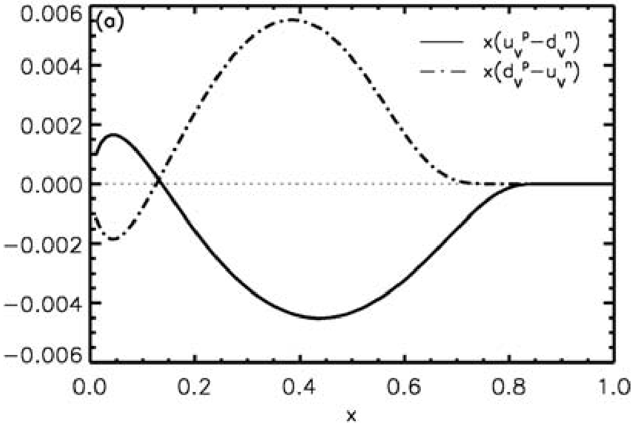

Fig. 2. Valence quark CSV contributions, $x\delta q_{\rm v}(x)$ vs. x. *Solid line*: $x\delta u_{\rm v}$; *dash-dot line*: $x\delta d_{\rm v}$. Calculated by Rodionov et al. [13] using MIT bag model wavefunctions, evolved to $Q^2 = 10$ GeV^2

The NuTeV group has measured NC and CC ν and $\bar\nu$ cross sections on iron [16] *[for more details, see talk by K. McFarland in these proceedings]*. They obtained the NC/CC ratios $R^\nu = 0.3916 \pm 0.0007$ and $R^{\bar\nu} = 0.4050 \pm 0.0016$, from which 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 value for the Weinberg angle obtained from electroweak (EW) processes near the Z pole, $\sin^2\theta_W = 0.2227 \pm 0.00037$ [17]. Such an effect can be interpreted as a 1.2% decrease in the left-handed coupling of light valence quarks to the weak neutral current. Davidson et al. [18] have examined possible contributions from "new physics" beyond the Standard Model. It is extremely difficult to find new particles that fit NuTeV without violating other experimental constraints, as several observables are constrained by very precise measurements, at or near the 0.1% level, in experiments near the Z pole [17]. Even modest success in removing the NuTeV anomaly, while leaving all other measurements within 1σ, can be achieved only with new particles whose masses, numbers, and couplings are very finely tuned – so-called "designer particles." Because of the serious difficulties in explaining the NuTeV result with particles outside the Standard Model, attention has focused on QCD effects within the Standard Model.

There are many QCD effects that must be taken into account [19]. For example, there is a correction due to the excess neutrons in Fe (iron is not an isoscalar target). Although the correction is large, it has been taken into account by NuTeV and should be well under control. Radiative corrections, which affect only CC reactions, are also substantial. These effects were calculated with a standard radiative correction model [20]. Recently Diener et al. have re-calculated the radiative corrections [21]. However, their calculation has yet to be incorporated into a reanalysis of the NuTeV data. The NuTeV group has also corrected for nuclear effects on the PDFs. There is still some uncertainty in the magnitude of such corrections; in particular, at present it is generally assumed that nuclear effects are identical for ν and charged-lepton DIS. Hirai et al. are currently calculating nuclear effects in neutrino reactions [22].

Finally, there is a possible contribution from a strange quark momentum asymmetry. The production of opposite-sign dimuons in ν and $\bar\nu$ reactions allows a separate extraction of s and $\bar s$ PDFs [23,24]. A difference in total momentum carried by s and $\bar s$ would affect the NuTeV result. Currently this has been analyzed by two groups; the CTEQ group extracts the strange PDFs in a global fit to high energy data [25], while the NuTeV group has analyzed the dimuon production cross Sects. [26,27]. At the moment the two results appear to disagree. The CTEQ analysis favors a positive momentum asymmetry $S_{\rm v} = \langle x(s - \bar s)\rangle$, which would remove roughly 1/3 of the NuTeV anomaly, while the NuTeV analysis is consistent with $S_{\rm v}$ either zero or slightly negative. The two groups are currently collaborating on the analyses, although they both agree that strange quark effects alone cannot remove the anomaly.

Here we will review the effects of isospin violation on the NuTeV anomaly. The correction to the PW ratio arising from isospin violation in the PDFs has the form

$$\Delta R^-_{CSV} \approx \left[1 - \frac{7}{3}\sin^2\theta_W\right] \frac{\delta U_{\rm v} - \delta D_{\rm v}}{2(U_{\rm v} + D_{\rm v})}. \tag{6}$$

Only valence quarks contribute to (6), and the correction depends on the second moment of valence PDFs, where $Q_{\rm v} \equiv \langle x(q - \bar q)\rangle$. The numerator of (6) is equal to the momentum asymmetry between up quarks and down quarks in an isoscalar nucleus, *i.e.*, $U_{\rm v}^p + U_{\rm v}^n - (D_{\rm v}^p + D_{\rm v}^n)$. However, estimates based on the PW ratio do not accurately predict contributions to the NuTeV result. The NuTeV group measures the NC/CC ratios R^ν and $R^{\bar\nu}$. Since these ratios have different cuts and acceptance corrections, one cannot simply combine them as in (5). To obtain the magnitude of a given effect on the NuTeV result for the Weinberg angle, it is necessary to fold that effect with functionals generated by NuTeV [27]. Thus, sea quark CSV makes a correction to the NuTeV extraction of the Weinberg angle, although it is much smaller than that from valence quark CSV. Using the best-fit MRST values for sea quark and valence quark CSV, would remove roughly 1/3 of the NuTeV anomaly. The value $\kappa = -0.6$, within the 90% confidence limit found by MRST, would completely remove the NuTeV anomaly, while the value $\kappa = +0.6$ would double the discrepancy. The MRST results show that isospin violating PDFs are able to completely remove the NuTeV anomaly in the Weinberg angle, or to make it twice as large, without serious disagreement with any of the data used to extract quark and gluon PDFs.

The model CSV predictions that we discussed earlier suggest that isospin violating corrections would tend to decrease the NuTeV anomaly for the Weinberg angle. Both the Rodionov [13] and Sather [14] theoretical models would remove about 1/3 of the NuTeV anomaly. There are other models that predict substantially smaller CSV effects on the NuTeV result [27,28,29], but all theoretical predictions are well within the phenomenological limits established by MRST. The magnitude of CSV effects allowed by the MRST fit makes isospin violation one of the only viable explanations for the NuTeV anomalous value for the Weinberg angle.

If CSV effects are sufficiently large to remove the Weinberg angle anomaly, such effects should be visible in various other experiments. Several possible experiments to test parton CSV were reviewed by Londergan and Thomas [30]. We briefly review three such possibilities. The first would be a comparison of Drell-Yan (DY) reactions from charged pions interacting with an isoscalar target. Comparison of, say, π^+-D and π^--D DY reactions would be sensitive to the presence of parton CSV. A study of these DY reactions [31] predicted CSV effects of about 2% in magnitude. Another experiment that could detect CSV effects would be semi-inclusive deep inelastic scattering (SIDIS) on an isoscalar target. A study of semi-inclusive π^+ and π^- leptoproduction on deuterium [32] predicted measurable effects from CSV. However, the ability to measure CSV effects in SIDIS reactions requires accurate knowledge of "favored" and "non-favored" fragmentation functions. In the studies of both DY and SIDIS reactions, the CSV effects were three times smaller than those necessary to explain the NuTeV anomaly. If isospin violating effects are really the explanation of the NuTeV effect, both of these reactions should produce effects at the several percent level. This is currently under investigation. A third possible test of parton isospin violation would be the measurement of W asymmetries in high-energy $p - D$ reactions. This could be carried out at RHIC if deuteron beams were available [33]. We are currently investigating the feasibility of this reaction, and the asymmetries that would be allowed by MRST phenomenological fits including CSV.

In conclusion, despite recent progress in constraining parton isospin violation, experimental data still allows parton CSV terms at the several percent level. This has been demonstrated by the MRST global fit that incorporates isospin violation, although the form of the CSV terms was fixed in their global fit. It is clearly of great interest to investigate this issue experimentally, either to decrease the allowed upper limits on isospin violating PDFs, or to measure isospin violating effects that might explain the anomalous NuTeV value for the Weinberg angle.

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