Eur Phys J A (2005) **24**, s2, 161–164
DOI: 10.1140/epjad/s2005-04-041-y

EPJ A direct
electronic only

Neutral currents and strangeness of the nucleon from the NuTeV experiment

Kevin S. McFarland[a]

University of Rochester, Rochester, NY 14610, USA

Received: 15 December 2004 / Published Online: 8 February 2005

Abstract. The NuTeV neutrino experiment ran in 1997-1998 at Fermilab and accumulated the world's highest statistics samples of high energy (20-300 GeV) separated neutrino and anti-neutrino interactions. The NuTeV collaboration has used this data to extract the electroweak parameter, $\sin^2\theta_W$, from the measurement of the ratios of neutral current to charged current neutrino and antineutrino deep inelastic scattering cross sections. This result, though consistent with previous neutrino electroweak measurements, is not consistent with predictions. One interpretation involves the possibility that the strange quark sea carries significantly more momentum in the nucleon than the anti-strange sea. We report on the direct study of this possibility from measurements of charged-current interactions on strange quarks in our neutrino and anti-neutrino beams.

PACS. 12.15.Mn Neutral Currents – 13.60.Hb Cross-sections in inelastic lepton-hadron scattering

1 Introduction and motivation

Neutrino scattering played a key role in establishing the structure of the Standard Model of electroweak unification, and it continues to be one of the most precise probes of the weak neutral current available experimentally today. With the availability of copious data from the production and decay of on-shell Z and W bosons for comparison, contemporary neutrino scattering measurements serve to validate the theory over many orders of magnitude in momentum transfer and provide one of the most precise tests of the weak couplings of neutrinos. In addition, precise measurements of weak interactions far from the boson poles are inherently sensitive to processes beyond our current knowledge, including possible contributions from leptoquark and Z' exchange [1] and new properties of neutrinos themselves [2].

The ratio of neutral current to charged current cross-sections for either ν or $\overline{\nu}$ scattering from isoscalar targets of u and d quarks can be written as [3]

$$R^{\nu(\overline{\nu})} \equiv \frac{\sigma(\overset{(-)}{\nu} N \to \overset{(-)}{\nu} X)}{\sigma(\overset{(-)}{\nu} N \to \ell^{-(+)} X)} = (g_L^2 + r^{(-1)} g_R^2), \quad (1)$$

where

$$r \equiv \frac{\sigma(\overline{\nu} N \to \ell^+ X)}{\sigma(\nu N \to \ell^- X)} \sim \frac{1}{2}, \quad (2)$$

and $g_{L,R}^2 \equiv (\epsilon_{L,R}^u)^2 + (\epsilon_{L,R}^d)^2$, isoscalar combinations of quark chiral couplings to the Z. Many corrections to 1 are required in a real target [4], but those most uncertain result from the suppression of the production of charm quarks in the target, which is the CKM-favored final state for charged-current scattering from the strange sea. This uncertainty has limited the precision of previous measurements of electroweak parameters in neutrino-nucleon scattering [5,6,7]. One way to reduce the uncertainty on electroweak parameters is to measure the observable

$$\begin{aligned} R^- &\equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\overline{\nu}_\mu N \to \overline{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\overline{\nu}_\mu N \to \mu^+ X)} \\ &= \frac{R^\nu - r R^{\overline{\nu}}}{1-r} = (g_L^2 - g_R^2), \end{aligned} \quad (3)$$

first suggested by Paschos and Wolfenstein [8] and valid under the assumption of equal momentum carried by the u and d valence quarks in the target. Since $\sigma^{\nu q} = \sigma^{\overline{\nu}\,\overline{q}}$ and $\sigma^{\overline{\nu} q} = \sigma^{\nu \overline{q}}$, the effect of scattering from sea quarks, which are symmetric under the exchange $q \leftrightarrow \overline{q}$, cancels in the difference of neutrino and anti-neutrino cross-sections. Therefore, the suppressed scattering from the strange sea does not cause large uncertainties in R^-. R^- is more difficult to measure than R^ν, primarily because the neutral current scatterings of ν and $\overline{\nu}$ yield identical observed final states which can only be distinguished through *a priori* knowledge of the initial state neutrino.

The experimental details and theoretical treatment of cross-sections in the NuTeV electroweak measurement are described in detail elsewhere [4]. In brief, we measure the experimental ratio of neutral current to charged current candidates in both a neutrino and anti-neutrino beam. A Monte Carlo simulation is used to express these exper-

---

[a] presenting on behalf of the NuTeV Collaboration

imental ratios in terms of fundamental electroweak parameters. This procedure implicitly corrects for details of the neutrino cross-sections and experimental backgrounds. For the measurement of $\sin^2\theta_W$, the sensitivity arises in the ν beam, and the measurement in the $\overline{\nu}$ beam is the control sample for systematic uncertainties, as suggested in the Paschos-Wolfenstein R^- of 3.

1.1 QCD corrections

Equations 1 and 3 assume targets symmetric under the exchange of u and d quarks, and that quark seas consist of quarks and anti-quarks with identical momentum distributions. The NuTeV analysis corrects for the significant asymmetry of d and u quarks that arises because the NuTeV target, which is primarily composed of iron, has a $5.74 \pm 0.02\%$ fractional excess of neutrons over protons. However, this correction is made under the assumption of isospin symmetry,

$$\overset{(-)}{u}_p(x) = \overset{(-)}{d}_n(x), \; \overset{(-)}{d}_p(x) = \overset{(-)}{u}_n(x)$$

This assumption, if significantly incorrect, could produce a sizable effect in the NuTeV extraction of $\sin^2\theta_W$ [9,10,11, 12]. Similarly, the cancellation of charm production from the strange quarks (3) assumes that the momentum distributions of the strange and anti-strange seas are identical, i.e., $s(x) = \overline{s}(x)$. NuTeV's analysis is done to leading order in pQCD, but perhaps surprisingly, the NLO corrections to R^- are very small [13,14,15].

Dropping the assumptions of symmetric heavy quark seas and isospin symmetry, but assuming small deviations in all cases, the effect of these deviations on R^- is [18]:

$$\begin{aligned}\delta R^- \approx\; & \frac{(U_p - \overline{U}_p - D_n + \overline{D}_n) - (D_p - \overline{D}_p - U_n + \overline{U}_n)}{2(U_p - \overline{U}_p + D_p - \overline{D}_p)} \\ & \times (3\Delta_u^2 + \Delta_d^2) \\ & + \frac{S_p - \overline{S}_p}{U_p - \overline{U}_p + D_p - \overline{D}_p}(2\Delta_d^2 - 3(\Delta_d^2 + \Delta_u^2)\epsilon_c), \quad (4)\end{aligned}$$

where $\Delta_{u,d}^2 = (\epsilon_L^{u,d})^2 - (\epsilon_R^{u,d})^2$, Q_N is the total momentum carried by quark type Q in nucleon N, and ϵ_c denotes the ratio of the scattering cross section from the strange sea including kinematic suppression of heavy charm production to that without kinematic suppression.

NuTeV does not exactly measure R^-, in part because it is not possible experimentally to measure neutral current reactions down to zero recoil energy. To parameterize the exact effect of the symmetry violations above, we define the functional $F[\sin^2\theta_W, \delta; x]$ such that

$$\Delta \sin^2\theta_W = \int_0^1 F[\sin^2\theta_W, \delta; x]\, \delta(x)\, dx, \quad (5)$$

for any symmetry violation $\delta(x)$ in PDFs. All of the details of the NuTeV analysis are included in the numerical evaluation of the functionals shown in Fig. 1. For this analysis, it can be seen that the level of isospin violation required to shift the $\sin^2\theta_W$ measured by NuTeV to its standard model expectation would be, e.g., $D_p - U_n \sim 0.01$ (about 5% of $D_p + U_n$), and that the level of asymmetry in the strange sea required would be $S - \overline{S} \sim +0.007$ (about 30% of $S + \overline{S}$).

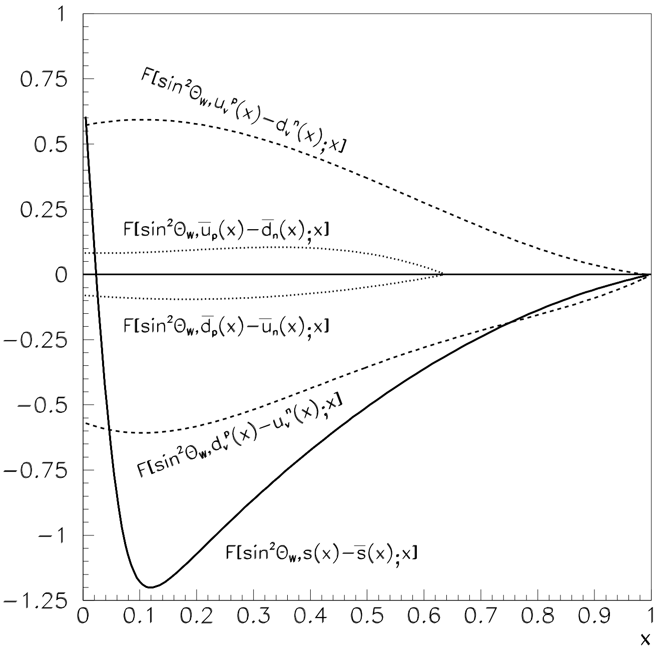

Fig. 1. The functionals describing the shift in the NuTeV $\sin^2\theta_W$ caused by not correcting the NuTeV analysis for isospin violating u and d valence and sea distributions or for $\langle s(x)\rangle \neq \langle \overline{s}(x)\rangle$. The shift in $\sin^2\theta_W$ is determined by convolving the asymmetric momentum distribution with the plotted functional

2 Electroweak results

As a test of the electroweak predictions for neutrino nucleon scattering, NuTeV performs a single-parameter fit to $\sin^2\theta_W$ with all other parameters assumed to have their standard values, e.g., standard electroweak radiative corrections with $\rho_0 = 1$. This fit determines

$$\begin{aligned}\sin^2\theta_W^{(\mathrm{on-shell})} &= 0.22773 \pm 0.00135(\mathrm{stat.}) \pm 0.00093(\mathrm{syst.}) \\ &\quad - 0.00022 \times \left(\frac{M_{\mathrm{top}}^2 - (175\ \mathrm{GeV})^2}{(50\ \mathrm{GeV})^2}\right) \\ &\quad + 0.00032 \times \ln\left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}}\right). \quad (6)\end{aligned}$$

A fit to the precision electroweak data, excluding neutrino measurements, predicts a value of 0.2227 ± 0.00037 [16, 17], approximately 3σ from the NuTeV measurement. In the on-shell scheme, $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$, where M_W and M_Z are the physical gauge boson masses; therefore, this result implies $M_W = 80.14 \pm 0.08$ GeV Although this deviation is statistically significant, it is not immediately apparent what the cause of this discrepancy might be.

We discuss, in turn, possibilities of new physics, nuclear effects, large isospin violation and an asymmetric strange sea.

2.1 New physics

The primary motivation for embarking on the NuTeV measurement was the possibility of observing hints of new physics in a precise measurement of neutrino-nucleon scattering. NuTeV is well suited as a probe of non-standard physics for two reasons: first, the precision of the measurement is a significant improvement, most noticeably in systematic uncertainties, over previous measurements [5,6,7], and second NuTeV's measurement has unique sensitivity to new processes when compared to other precision data. In particular, NuTeV probes weak processes far off-shell, and thus is sensitive to other tree level processes involving exchanges of heavy particles. Also, the initial state particle is a neutrino, and neutrino couplings are the most poorly constrained by the Z^0 pole data, since they are primarily accessed *via* the measurement of the Z invisible width. An often useful low-energy parameterization of new physics is to consider a unit-coupling "contact interaction" in analogy with the Fermi effectively theory of low-energy weak interactions. Assuming a contact interaction described by a Lagrangian of the form

$$-\mathcal{L} = \sum_{H_q \in \{L,R\}} \frac{\pm 4\pi}{\left(\Lambda^{\pm}_{LH_q}\right)^2} \times \\ \{\overline{l_L}\gamma^{\mu} l_L \overline{q_{H_q}}\gamma_{\mu} q_{H_q} + l_L \gamma^{\mu} \overline{l_L}\,\overline{q_{H_q}}\gamma_{\mu} q_{H_q} + \text{C.C.}) \quad (7)$$

the NuTeV result can be explained by an interaction with mass scale $\Lambda^{+}_{LL} \approx 4 \pm 0.8$ TeV. However, *post hoc* it appears that well motivated and complete models for such an interaction seem to be difficult to find [12].

An extra $U(1)$ gauge group giving rise to a heavy Z' boson is a possibility [12,19], but the $U(1)$ gauge group suggested by NuTeV would not necessarily be one motivated by models of unification of known forces [1]. There are few other precision measurements of neutrino neutral current interactions. Measurements of neutrino-electron scattering from the CHARM II experiment [20] and the direct measurement of $\Gamma(Z \to \nu\overline{\nu})$ from the observation of $Z \to \nu\overline{\nu}\gamma$ at the Z^0 pole [16] provide measurements of a few percent precision. The two most precise measurements come from the inferred Z invisible width [16] and the NuTeV result. Both of the precise rate measurements are significantly below the expectation. Again, models how such a deviation of neutrino couplings might fit against other constraints from the data are difficult to find, and the most complete attempts come from models which mix heavy and light neutrinos to form the eigenstates of the neutral weak interaction [21].

2.1.1 Nuclear Effects

It has been suggested by several authors, correctly, that differences in nuclear effects between charged and neutral current neutrino scattering could affect the NuTeV $\sin^2\theta_W$ analysis. There are constraints on process dependent nuclear effects, notably the agreement between F_2 from charged-lepton and neutrino charged-current scattering [22]. However, effects such Vector Meson Dominance in shadowing [23] or models of anti-shadowing [24] could still affect the NuTeV result. The former model predicts large increases in R^{ν} and $R^{\overline{\nu}}$ as measured by NuTeV of 0.6% and 1.2%, respectively. This effect, however, largely cancels in R^{-}, and furthermore the NuTeV $\sin^2\theta_W$ data itself disfavors this model through its separate measurements of R^{ν} and $R^{\overline{\nu}}$, which are both below predictions, while this model *increases* those very predictions. The latter model of anti-shadowing would primarily effect $R^{\overline{\nu}}$ and increase it modestly. This effect would be consistent with, though not favored by, the NuTeV data, and although it could reduce slightly the measured $\sin^2\theta_W$ from R^{-}, it would not improve the overall agreement of the NuTeV R^{ν} and $R^{\overline{\nu}}$ with the data.

2.2 Isospin violation

Several recent classes of models predict isospin violation in the nucleon [9,10,11]. The earliest estimation in the literature, a bag model calculation [9], predicts large valence asymmetries of opposite sign in $u_p - d_n$ and $d_p - u_n$ at all x, which would produce a shift in the NuTeV $\sin^2\theta_W$ of -0.0020. A more complete calculation done by Thomas *et al.* [10] concludes that asymmetries at very high x are larger, but the asymmetries at moderate x are smaller and of opposite sign at low x. This calculation is sensitive to the amount of smearing allowed in the energy of the remaining diquark at the bag scale after scattering, agreeing qualitatively with the Sather result with no smearing, but reducing the effect to a negligible -0.0001 when assuming smearing of order Λ_{QCD}. The effect is also evaluated in the Meson Cloud model [11], and there the asymmetries are much smaller at all x, resulting in a modest shift in the NuTeV $\sin^2\theta_W$ of $+0.0002$. Finally, Thorne *et al.* [25] have proposed that isospin violation may arise from QED corrections to PDFs, and have estimated the possible size of the effect in R^{-} to be ~ -0.002. However, this calculation is very sensitive to assumptions about the quark mass, and the value above assumes quark masses of a few MeV are appropriate. The assumption of constituent quark masses would drastically reduce the size but would retain the sign of the effect.

Models for isospin violation aside, the NuTeV data itself cannot provide a significant independent constraint on this form of isospin violation. A recent global analysis has also attempted to constrain this possibility, but found no sufficiently significant constraint. It allows isospin violation large enough to move NuTeV into agreement with prediction or large enough to double the discrepancy [26]. We conclude that NuTeV may have indeed found strong evidence for large (compared to even generous predictions) isospin violation in PDFs in a direction favored by most models, but that there is no independent evidence to support this hypothesis.

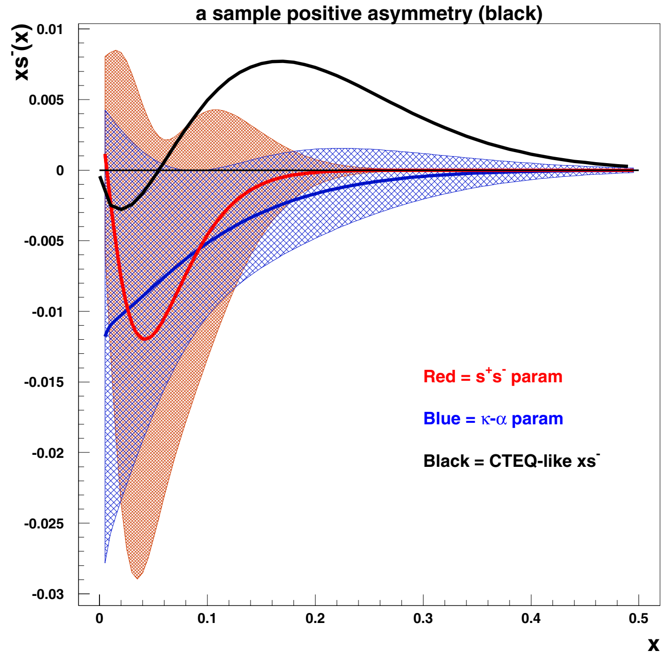

Fig. 2. NuTeV's results for the strange quark momentum asymmetry, $s(x) - \overline{s}(x)$, using different parameterizations. The "$\kappa - \alpha$" parameterization, allowing differences in magnitude and power in (1-x) is shown in *blue*; a parameterization suggested by CTEQ for s^+,s^- is shown in *red*; and a sample positive asymmetry using that parameterization with the central value of [31] is shown in *black*

2.2.1 Strange Sea Asymmetry

If the strange sea is generated by purely perturbative QCD processes, then neglecting electromagnetic effects, one expects $\langle s(x) \rangle = \langle \overline{s}(x) \rangle$. However, it has been noted that non-perturbative QCD effects can generate a significant momentum asymmetry between the strange and anti-strange seas [27,28,29,30]. Outside the context of the NuTeV electroweak data, measurements of this momentum asymmetry constrain the properties of the intrinsic strange sea of the nucleon and helps to discriminate among the models suggested above.

By measuring the processes $\nu_N, \overline{\nu}_N \rightarrow \mu^+\mu^- X$, the CCFR and NuTeV experiments constrain the difference between the momentum distributions of the strange and anti-strange seas. A recent analysis from the CTEQ collaboration [31] has claimed that this data favors a positive $S - \overline{S}$, perhaps large enough to explain one sigma of the NuTeV discrepancy. However, the NuTeV fully NLO QCD analysis [32], does not confirm these results and instead weakly prefers negative $S - \overline{S}$, as illustrated in Fig. 2. The constraint represented by this analysis, with an uncertainty that translates to less than one NuTeV standard deviation in $\sin^2\theta_W$, makes it unlikely that a positive $S - \overline{S}$ is responsible for what we observe.

Acknowledgements. We gratefully acknowledge support for this work from the U.S. Department of Energy, the National Science Foundation and the Alfred P. Sloan Foundation. The NuTeV experiment benefited greatly from significant contributions from the Fermilab Particle Physics, Computing, Technical and Beams Divisions.

References

1. P. Langacker et al.: Rev. Mod. Phys. **64**, 87 (1991)
2. K.S. McFarland, D. Naples et al.: Phys. Rev. Lett. **75**, 3993 (1995)
3. C.H. Llewellyn Smith: Nucl. Phys. B **228**, 205 (1983)
4. G.P. Zeller et al.: Phys. Rev. Lett. **88**, 091802 (2002)
5. K.S. McFarland et al. Eur. Phys. Jour. **C1**, 509 (1998)
6. A. Blondel et al.: Zeit. Phys. C **45**, 361 (1990)
7. J. Allaby et al. Zeit. Phys. C **36**, 611 (1985)
8. E.A. Paschos, L. Wolfenstein: Phys. Rev. D **7**, 91 (1973)
9. E. Sather: Phys. Lett. B **274**, 433 (1992)
10. E.N. Rodionov, A.W. Thomas, J.T. Londergan: Mod. Phys. Lett. A **9**, 1799 (1994)
11. F. Cao, A.I. Signal: Phys. Rev. C **62**, 015203 (2000)
12. S. Davidson, S. Forte, P. Gambino, N. Rius, A. Strumia: hep-ph/0112302
13. K. McFarland, S.-O. Moch: Proceedings of Mini-Workshop on Electroweak Precision Data and the Higgs Mass, hep-ph/0306052
14. S. Kretzer: Procedings of the Rencontres de Moriond on QCD and High-Energy Hadronic Interactions, hep-ph/0405221
15. B. Dobrescu, R.K. Ellis: Phys. Rev. D **69**, 114014 (2004)
16. "A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model", CERN-EP/2001-98, hep-ex/0112021
17. M. Grünewald: private communication, for the fit of [16] without neutrino-nucleon scattering data included
18. G.P. Zeller et al.: "On the effect of asymmetric strange seas and isospin-violating parton distribution functions on $\sin^2\theta_W$ measured in the NuTeV experiment," hep-ex/0203004
19. E. Ma, D.P. Roy: Phys. Rev. D **65**, 075021 (2002)
20. P. Vilain et al: Phys. Lett. B **335**, 248 (1994)
21. W. Loinaz, N. Okamura, T. Takeuchi, L.C.R. Wijewardhana: Phys. Rev. D **67**, 073012 (2003)
22. U.K. Yang et al., [CCFR/NuTeV Collaboration]: Phys. Rev. Lett. **86**, 2742 (2001)
23. G.A. Miller, A.W. Thomas: hep-ex/0204007
24. S. Brodsky, I. Schmidt, J.-Y. Yang: SLAC-PUB-9677, USM-TH-136, hep-ph/0409279
25. A. Martin, R. Roberts, W. Stirling, R. Thorne: IPPP-04-62, DCPT-04-124, CAVENDISH-HEP-2004-28, hep-ph/0411040
26. R.S. Thorne (Cambridge U.): Int. J. Mod. Phys. A **19**, 1074 (2004)
27. A.I. Signal, A.W. Thomas: Phys. Lett. B **191**, 205 (1987)
28. M. Burkardt, B.J. Warr: Phys. Rev. D **45**, 958 (1992)
29. S. Brodsky, B. Ma: Phys. Lett. B **381**, 317 (1996)
30. W. Melnitchouk, M. Malheiro: Phys. Lett. B **451**, 224 (1999)
31. S. Kretzer et al.: Phys. Rev. Lett. **93**, 041802 (2004); F. Olness et al.: MSU-HEP-030701, BNL-NT-03-17, RBRC-329, hep-ph/0312323
32. D. Mason [NuTeV Collaboration]: Proceedings of 39th Rencontres de Moriond on QCD and High-Energy Hadronic Interactions, hep-ex/0405037