Fermilab FERMILAB-Conf-02/407-E January 2004

A DEPARTURE FROM PREDICTION: ELECTROWEAK PHYSICS AT NUTEV

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Abstract

The NuTeV experiment has performed precision measurements of the ratio of neutral-current to charged-current cross-sections in high rate, high energy neutrino and anti-neutrino beams on a dense, primarily steel, target. The separate neutrino and anti-neutrino beams, high statistics, and improved control of other experimental systematics, allow the determination of electroweak parameters with significantly greater precision than past νN scattering experiments. Our null hypothesis test of the standard model prediction measures $\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$, a value which is 3.0σ above the prediction. We discuss possible explanations for and implications of this discrepancy.

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 Lagrangian for weak neutral current ν–q scattering can be written as

$$\begin{aligned}\mathcal{L} &= -\frac{G_F\rho_0}{\sqrt{2}}(\overline{\nu}\gamma^\mu(1-\gamma^5)\nu) \\ &\quad\times\left(\epsilon_L^q\overline{q}\gamma_\mu(1-\gamma^5)q+\epsilon_R^q\overline{q}\gamma_\mu(1+\gamma^5)q\right), \end{aligned} \tag{1}$$

where deviations from $\rho_0 = 1$ describe non-standard sources of SU(2) breaking, and $\epsilon^q_{L,R}$ are the chiral quark couplings [1] For the weak charged current, $\epsilon^q_L = I^{(3)}_{\rm weak}$ and $\epsilon^q_R = 0$, but for the neutral current ϵ^q_L and ϵ^q_R each contain an additional term, $-Q\sin^2\theta_W$, where Q is the quark's electric charge in units of e.

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)]

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

where

$$r \equiv \frac{\sigma(\overline{\nu}N \to \ell^+ X)}{\sigma(\nu N \to \ell^- X)} \sim \frac{1}{2}, \tag{3}$$

and $g^2_{L,R} = (\epsilon^u_{L,R})^2 + (\epsilon^d_{L,R})^2$. Many corrections to Equation 2 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

[1] Note that although we use a process-independent notation here for a tree-level ρ, radiative corrections to ρ depend slightly on the particles involved in the weak neutral interaction. In this case, $\rho \equiv \sqrt{\rho^{(\nu)}\rho^{(q)}}$.

uncertainty on electroweak parameters is to measure the observable

$$\begin{aligned} R^- &\equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\overline{\nu}_\mu N \to \overline{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\overline{\nu}_\mu N \to \mu^+ X)} \\ &= \frac{R^\nu - r\,R^{\overline{\nu}}}{1-r} = (g_L^2 - g_R^2), \end{aligned} \tag{4}$$

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 experimental 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 Eqn. 4. For simulataneous fits to two electroweak parameters, e.g., $\sin^2\theta_W$ and ρ or left and right handed couplings, this redundant control of systematics cannot be realized.

2 Result

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

$$\begin{aligned} \sin^2\theta_W^{(\mathrm{on-shell})} &= 0.22773 \pm 0.00135(\mathrm{stat.}) \pm 0.00093(\mathrm{syst.}) \\ &- 0.00022 \times \left(\frac{M_{\mathrm{top}}^2 - (175\ \mathrm{GeV})^2}{(50\ \mathrm{GeV})^2}\right) \\ &+ 0.00032 \times \ln\left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}}\right). \end{aligned} \tag{5}$$

The small dependences in M_{top} and M_{Higgs} result from radiative corrections as determined from code supplied by Bardin [9] and from V6.34 of ZFITTER [10]; however, it

should be noted that these effects are small given existing constraints on the top and Higgs masses [11]. A fit to the precision electroweak data, excluding neutrino measurements, predicts a value of 0.2227 ± 0.00037 [11, 12], 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 [2]. The world-average of the direct measurements of M_W is 80.45 ± 0.04 GeV [11]. The fact that the NuTeV $\sin^2\theta_W^{(\mathrm{on-shell})}$ deviates so substantially from M_W makes it difficult to explain the difference between NuTeV and the standard model prediction in terms of oblique radiative corrections.

Although NuTeV was primarily designed to measure $\sin^2\theta_W^{(\mathrm{on-shell})}$ using the Paschos-Wolfenstein relationship, it is also possible to fit for the single parameter, ρ_0. As noted above, the mechanism by which the Paschos-Wolfenstein relationship reduces systematic uncertainties in the $\sin^2\theta_W$ fit is evident in the fact that R^ν only is sensitive to $\sin^2\theta_W$ and thus $R^{\overline{\nu}}$ essentially measures systematics common to the ν and $\overline{\nu}$ beams. Because R^ν and $R^{\overline{\nu}}$ are both sensitive to ρ_0, there is less control of theoretical systematics than can be achieved with the $\sin^2\theta_W$ measurement, and uncertainties on ρ_0 are therefore larger. This fit obtains

$$\begin{aligned}\rho_0 &= 0.9942 \pm 0.0013(\mathrm{stat.}) \pm 0.0016(\mathrm{syst.}) \\ &+ 0.00006 \times \left(\frac{M_{\mathrm{top}}^2 - (175\ \mathrm{GeV})^2}{(50\ \mathrm{GeV})^2}\right) \\ &- 0.00016 \times \ln\left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}}\right). \end{aligned} \quad (6)$$

Note that these two results are highly correlated; a simultaneous fit to $\sin^2\theta_W$ and ρ_0 finds:

$$\rho_0 = 0.99789 \pm 0.00405,\ \sin^2\theta_W = 0.22647 \pm 0.00311, \quad (7)$$

with a correlation coefficient of 0.850 between the two parameters. This suggests one but not both of $\sin^2\theta_W^{(\mathrm{on-shell})}$ or ρ_0 may be consistent with expectations, and that NuTeV is unable to distinguish between these two possibilities with significant confidence.

Finally, we have also performed a two-parameter fit in terms of the isoscalar combinations of effective neutral-current quark couplings $(g_{L,R}^{\mathrm{eff}})^2 = (u_{L,R}^{\mathrm{eff}})^2 + (d_{L,R}^{\mathrm{eff}})^2$. The effective couplings, which describe observed experimental rates when the processes described by Eqn. 1 are calculated without electroweak radiative corrections, are mea-

[2] As noted above, this extraction of $\sin^2\theta_W^{(\mathrm{on-shell})}$ is done assuming radiative corrections from the standard model as parameterized from α_{EM}, G_F, M_Z, m_{top} and m_{Higgs} from fits to the electroweak data. An alternative approach, would be to fit for M_W by determining regions of m_{top} and m_{Higgs} favored by the NuTeV data and then using those to extract the standard model prediction.

sured at $\langle q^2 \rangle \sim -20$ GeV^2. We find [3]:

$$(g_L^{\rm eff})^2 = 0.30005 \pm 0.00137, \ (g_R^{\rm eff})^2 = 0.03076 \pm 0.00110, \tag{8}$$

with a correlation coefficient of -0.017. The predicted values from Standard Model parameters corresponding to the electroweak fit described earlier [11, 12] are $(g_L^{\rm eff})^2 = 0.3042$ and $(g_R^{\rm eff})^2 = 0.0301$. Note that due to the asymmetry between the strange and charm seas and to the slight excess of neutrons in our target, the NuTeV result is weakly affected ($\sim 1/30$ the sensitivity of $(g_{L,R}^{\rm eff})^2$) by the isovector combinations of couplings, $(\delta_{L,R}^{\rm eff})^2 = (u_{L,R}^{\rm eff})^2 - (d_{L,R}^{\rm eff})^2$. The results above assume standard model values for $(\delta_{L,R}^{\rm eff})^2$.

3 Interpretation

The NuTeV $\sin^2\theta_W$ result is approximately three standard deviations from the prediction of the standard electroweak theory. This, by itself is surprising; however, it is not immediately apparent what the cause of this discrepancy might be. We discuss, in turn, the possibility that the NuTeV result is a statistical fluctuation among many precision results, the possibility that unexpected parton asymmetries in the NuTeV affect the result, and finally possibilities for non-standard physics which could be appearing in the anomalous NuTeV value.

3.1 Impact on Standard Model Fits

For fits assuming the validity of the Standard Model, it is appropriate to consider the *a priori* null hypothesis test chosen in the proposal of the NuTeV experiment, namely the measurement of $\sin^2\theta_W^{(\rm on-shell)}$. A fit to precision data [4], including NuTeV, has been performed by the LEPEWWG [11], and the contribution of each measurement to the χ^2 and final Higgs mass from this fit is shown in Figure 1. The global χ^2, which has significant contributions from NuTeV's $\sin^2\theta_W$ measurement and $A_{FB}^{0,b}$ from LEP I, is a rather unhealthy 28.8 for 15 degrees of freedom. The probability of the fit χ^2 being above 28.8 is 1.7%. Without NuTeV, this probability of the resulting χ^2 is a plausible 14%. This suggests that in the context of all the precision data, as compiled by the LEPEWWG, the

[3] Note that these coupling results are slightly different ($<< 1\sigma$) than the value given in the published NuTeV result [4] due to a numerical error.

[4] It is a tautology, but still worth noting explicitly, that certain choices about what constitutes "the precision data" must be made in order to make such a global analysis. Some choices that are made in compiling this data, for example, not listing the W mass for each experiment separately, decrease the number of degrees of freedom without significantly decreasing the global χ^2. Other choices taken, for example choosing particular re-evaluations of the central value and uncertainties [13, 14, 15, 16], rather than others [17] in the atomic parity violation measurement [18] of Q_W^{Cs}, decrease the global χ^2.

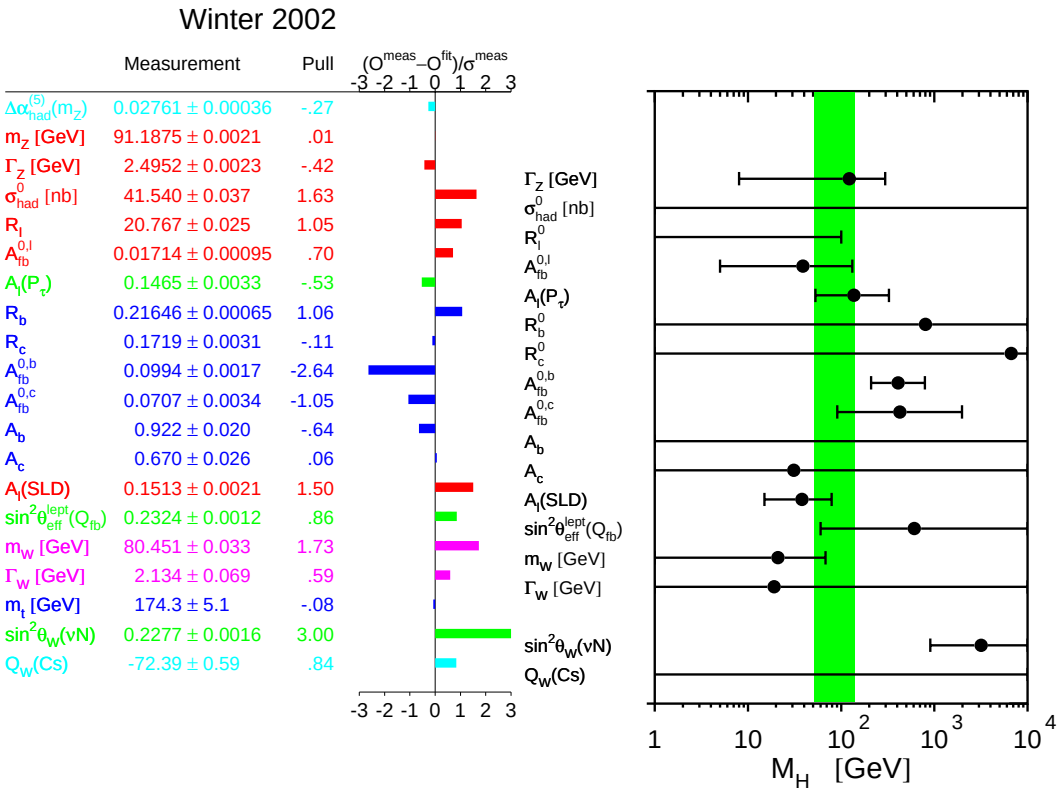

Figure 1: *The precision data, as compiled and fit by the LEPEWWG* [11]. *The global fit* χ^2 *is* $28.8/15$. *Most of the data is consistent with a low Higgs mass, except* $A_{FB}^{0,b}$ *and the NuTeV* $\sin^2\theta_W$.

NuTeV result is still a statistical anomaly sufficient to spoil the fit if the standard model is assumed.

This large χ^2 is dominated by two moderately discrepant measurements, namely $A_{FB}^{0,b}$ and the NuTeV $\sin^2\theta_W$, and if one or both are discarded arbitrarily, then the data is reasonably consistent with the standard model. However, the procedure of merely discarding one or both of these measurements to make the fit "work" is clearly not rigorous. Furthermore, the potential danger of such a procedure has been noted previously in the literature. For example, if $A_{FB}^{0,b}$ were disregarded, then the most favored value of the Higgs mass from the fit would be well below the direct search limits [19].

Motivated by this large global χ^2 of the precision electroweak data, we attempt to find other explanations for the discrepancy in the NuTeV $\sin^2\theta_W$ measurement.

3.2 Unexpected QCD Effects

As noted above, corrections to Eqns. 2 and 4 are required to extract electroweak parameters from neutrino scattering on the NuTeV target. In particular, these equations 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 assumption is made under the assumption of isospin symmetry, i.e., $\overset{(-)}{u}_p(x) = \overset{(-)}{d}_n(x)$, $\overset{(-)}{d}_p(x) = \overset{(-)}{u}_n(x)$. This assumption, if significantly incorrect, could produce a sizable effect in the NuTeV extraction of $\sin^2\theta_W$ [20, 21, 22, 23].

Dropping the assumptions of symmetric heavy quark seas, isospin symmetry and a target symmetric in neutrons and protons, but assuming small deviations in all cases, the effect of these deviations on R^- is [24]:

$$\begin{aligned}
\delta R^- \;\approx\; & -\delta N \left(\frac{U_p - \overline{U}_p - D_p + \overline{D}_p}{U_p - \overline{U}_p + D_p - \overline{D}_p} \right) (3\Delta_u^2 + \Delta_d^2) \\
& + \frac{(U_p - \overline{U}_p - D_n + \overline{D}_n) - (D_p - \overline{D}_p - U_n + \overline{U}_n)}{2(U_p - \overline{U}_p + D_p - \overline{D}_p)} (3\Delta_u^2 + \Delta_d^2) \\
& + \frac{S_p - \overline{S}_p}{U_p - \overline{U}_p + D_p - \overline{D}_p} (2\Delta_d^2 - 3(\Delta_d^2 + \Delta_u^2)\epsilon_c),
\end{aligned} \tag{9}$$

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 the neutron excess, $\delta N \equiv (A - 2Z)/A$. 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. The first term is the effect of the neutron excess, which is accounted for in the NuTeV analysis; the second is the effect of isospin violation and the third is the effect of an asymmetric strange sea.

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

$$\Delta\sin^2\theta_W = \int_0^1 F[\sin^2\theta_W, \delta; x]\, \delta(x)\, dx, \tag{10}$$

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 Figure 2. For this analysis, it can be seen that the level of isospin violation required to shift the $\sin^2\theta_W$ measured

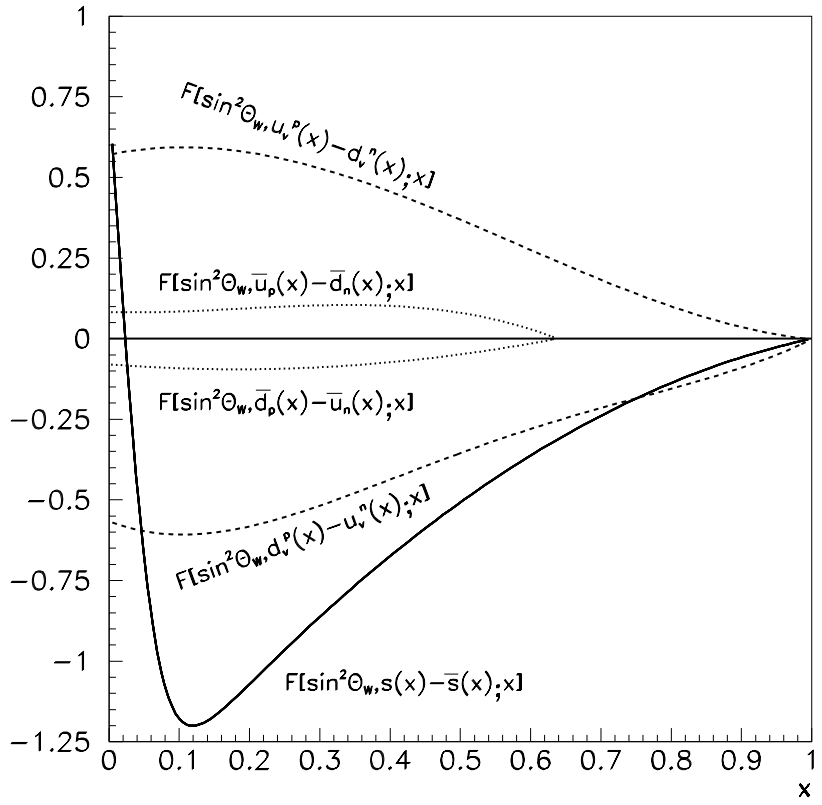

Figure 2: *The functionals describing the shift in the NuTeV* $\sin^2\theta_W$ *caused by not correcting the NuTeV analysis for isospin violating* u *and* d *valence and sea distributions or for* $\langle s(x)\rangle \neq \langle \overline{s}(x)\rangle$*. The shift in* $\sin^2\theta_W$ *is determined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

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 $S + \overline{S}$).

3.2.1 Isospin Violations

Several recent classes of non-perturbative models predict isospin violation in the nucleon [20, 21, 22]. The earliest estimation in the literature, a bag model calculation [20], 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. However, this estimate neglects a number of effects, and a complete bag model calculation by Thomas *et al.* [21] concludes that asymmetries at very high x are larger, but the asymmetries at moderate x are smaller and of opposite sign at low x, thereby reducing the shift in $\sin^2\theta_W$ to a negligible -0.0001. Finally, the effect is also evaluated in the Meson Cloud model [22], and there the asymmetries are much smaller at all x, resulting in a modest shift in the NuTeV $\sin^2\theta_W$ of $+0.0002$.

Models aside, the NuTeV data itself cannot provide a significant independent constraint on this form of isospin violation. However, because PDFs extracted from neutrino data (on heavy targets) are used to separate sea and valence quark distributions which affect observables at hadron colliders [25], global analyses of PDFs including the possibility of isospin violation may be able to constrain this possibility experimentally.

3.2.2 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 [26, 27, 28, 29].

By measuring the processes $\nu_N, \overline{\nu}_N \to \mu^+\mu^- X$ the CCFR and NuTeV experiments constrain the difference between the momentum distributions of the strange and anti-strange seas. Within the NuTeV cross-section model model, this data implies a *negative* asymmetry [24],

$$S - \overline{S} = -0.0027 \pm 0.0013, \tag{11}$$

or an asymmetry of $11 \pm 6\%$ of $(S + \overline{S})$. Therefore, dropping the assumption of strange-antistrange symmetry results in an *increase* in the NuTeV value of $\sin^2\theta_W$,

$$\Delta\sin^2\theta_W = +0.0020 \pm 0.0009. \tag{12}$$

The initial NuTeV measurement, which assumes $\langle s(x)\rangle = \langle \overline{s}(x)\rangle$, becomes

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2297 \pm 0.0019.$$

Hence, if we use the experimental measurement of the strange sea asymmetry, the discrepancy with the standard model is increased to 3.7σ significance.

3.2.3 Nuclear Shadowing

A recent comment in the literature [30] has claimed, correctly, that if shadowing were significantly different between charged and neutral current neutrino scattering, this would affect the NuTeV $\sin^2\theta_W$ analysis. The authors offer a Vector Meson Dominance (VMD) model of shadowing in which such an effect might arise. This model predicts a large enhancement of shadowing at low Q^2 which is not observed in deep inelastic scattering data. The most precise data that overlaps the low x and Q^2 kinematic region of NuTeV comes from NMC [31], which observed a logarithmic Q^2 dependence of the shadowing effect as predicted by perturbative QCD.

Furthermore, shadowing, a low x phenomenon, largely affects the sea quark distributions which are common between ν and $\overline{\nu}$ cross-sections, and therefore cancel in R^-. The NuTeV analysis, which uses ν and $\overline{\nu}$ data at $< Q^2 >$ of 25 and 16 GeV^2, respectively, is far away from the VMD regime, and therefore the effect even of this VMD model is small, increasing the prediction for the NuTeV measured R^ν and $R^{\overline{\nu}}$ by 0.6% and 1.2%, respectively. Finally, 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.

3.3 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.

In considering models of new physics, the "model-independent" coupling measurement discussed in Section 2 is the best guide for evaluating non-standard contributions to the NuTeV measurements. An interesting thing to note about these measurements is that they suggest a large deviation in the left-handed chiral coupling to the target quarks, while the right-handed coupling is as expected. Such a pattern of changes in couplings is consistent with either a hypothesis of loop corrections that effect the weak process itself or another tree level contribution that contributes primarily to the left-handed coupling [5]. Chiral coupling deviations are often parameterized in terms of the mass scale for 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

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

the NuTeV result can be explained by an interaction with mass scale $\Lambda^{+}_{LL} \approx 4 \pm 0.8$ TeV.

3.3.1 Interactions from Extra U(1)

Phenomenologically, an extra $U(1)$ gauge group which gives rise to interactions mediated by a heavy Z' boson, $m_{Z'} \gg m_Z$, is an attractive model for new physics. In general, the couplings associated with this new interaction are arbitrary, although specific models in which a new $U(1)$ arises may provide predictions or ranges of predictions for these couplings. An example of such a model is an $E(6)$ gauge group, which encompasses the $SU(3) \times SU(2) \times U(1)$ of the standard model and also predicts several additional $U(1)$ subgroups which lead to observable interactions mediated by Z' bosons [1, 32, 33]. Before the NuTeV measurement, several authors had suggested in the literature that the other precision electroweak data favored the possibility of a Z' boson [34, 35, 36, 37].

We have analyzed the effect of $E(6)$-predicted Z' bosons on the NuTeV measurement of the chiral couplings. As is illustrated in Figure 3, the effect of these bosons in the case where the standard model Z and Z' do not mix is primarily on the right-handed coupling. It is possible to reduce the left-handed coupling somewhat by allowing $Z - Z'$ mixing; however, this possibility is severely constrained by precision data at the Z^0 pole [36].

More generally, a Z' with couplings of the same magnitude as the Z but leading to a destructive interference with the Z exchange could explain the NuTeV measurement

[5] It has been noted many times in the literature that the $A^{0,b}_{FB}$ deviation, combined with other constraints on b quark neutral current couplings implies a shift in the small *right-handed* coupling. Such a shift is not consistent with the hypothesis of a loop-induced correction, either standard or non-standard.

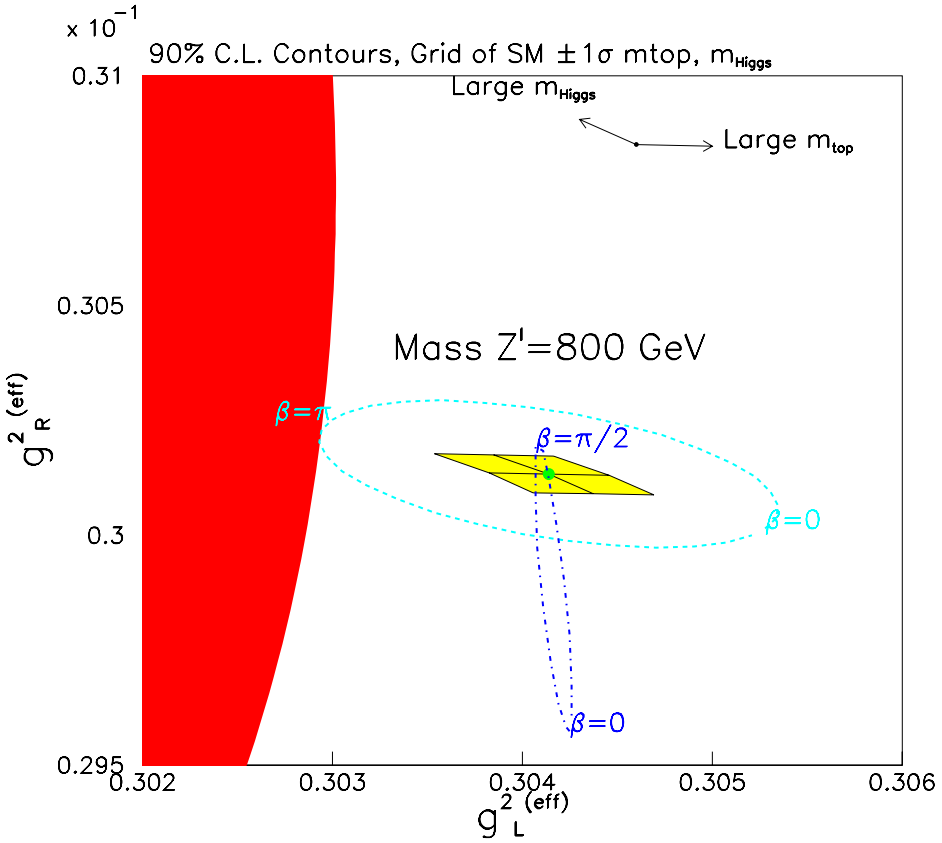

Figure 3: *The effect of $E(6)$ Z' bosons on the NuTeV measurement of $(g_L^{\rm eff})^2$ and $(g_R^{\rm eff})^2$. The parameter β chooses which of the possible $U(1)$ subgroups contributed to the observed Z'. The standard model prediction is the green point, surrounded by a grid of $\pm 1\sigma$ top and Higgs mass variations. The upright dark ellipse around shows the effect of an unmixed Z'; the lighter ellipse shows the effect of $Z - Z'$ a mixing of 0.003, which is already severely constrained by the Z^0 pole data.*

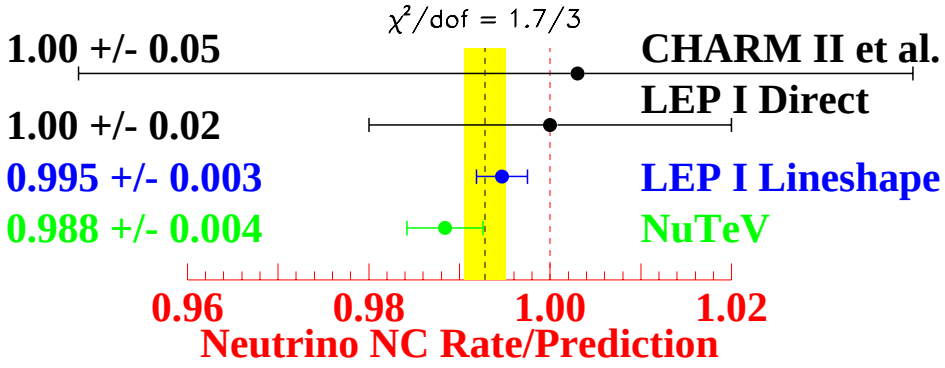

Figure 4: *Measurements of the neutrino current coupling, interpreted as a neutrino neutral current interaction rate ($\propto \rho^{(\nu)}$). The precise measurements, $\Gamma(Z \to \nu\overline{\nu})$ at LEP I and the NuTeV measurement of ρ_0^2 are both below expectation.*

if the Z' mass were in the range $\approx$ 1–1.5 TeV. Current limits from the TeVatron experiments on such Z' are approximately 0.7 TeV [38, 39]. Several authors have also recently discussed other $U(1)$ extensions in the context of the NuTeV result and found significant effects [23, 40].

3.3.2 Anomalous Neutrino Neutral Current

There are few precision measurements of neutrino neutral current interactions. Measurements of neutrino-electron scattering from the CHARM II experiment [41] 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 [11] provide measurements of a few percent precision. The two most precise measurements come from the inferred Z invisible width [11] and the NuTeV result when interpreted as a measurement of ρ_0^2 (see Section 2). As is shown in Figure 4, both of the precise rate measurements are significantly below the expectation. Although this is not a model-independent observation, it is nevertheless interesting to note this connection between two of the discrepant pieces of precision electroweak data.

4 Summary

The NuTeV experiment has performed a measurement of $\sin^2\theta_W$, and finds a deviation of three standard deviations from the null hypothesis which assumes the validity of the

standard model of electroweak interactions. Motivated by the significance of this discrepancy, we study both conventional and new physics explanations. Several possibilities exist, although none is theoretically compelling or has sufficient independent supporting evidence to be a clear favorite. Therefore, the cause of this result remains a puzzle.

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 benefitted greatly from significant contributions from the Fermilab Particle Physics, Computing, Technical and Beams Divisions. In addition, we thank Stan Brodsky, Jens Erler, Martin Grünewald, Paul Langackger, Michael Peskin, Jon Rosner and Tony Thomas for useful input and discussions.

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