

NuTeV and Neutrino Properties

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Abstract

This report explores the results and implications of the weak mixing angle measurement made by the NuTeV neutrino experiment at Fermilab. The NuTeV experiment, using a technique that exploits muon neutrino and antineutrino data to determine the neutral current to charged current ratios, R^ν and $R^{\bar{\nu}}$, has made the most precise measurement of the weak mixing angle using neutrinos as probes. The result gives a value of $\sin^2\theta_W(\text{on-shell}) = 0.2277 \pm 0.0016$ which is about three standard deviations larger than the standard model prediction of 0.2227. Various interpretations for the source of the anomaly are considered including changes to the inputs to the standard model predictions, unexpected symmetry violations, or new physics interpretations involving unanticipated neutrino properties or new particle contributions. Speculations on new precision measurements to further explore this region are also presented, including, for example, a future reactor neutrino-electron elastic scattering measurement. At present the discrepancy is unexplained, but could point to some as yet undiscovered broken quark symmetry, or towards new physics associated with neutrino interactions or mixings.

1 Introduction

For more than thirty years, starting with the discovery of neutral currents using neutrino beams at CERN in 1973, electroweak measurements have provided the most important and precise tests of the standard model (SM) of particle physics. A combination of theoretical and experimental progress has now allowed a new era of precision studies. On the theoretical side, the phenomenology is well understood and high order corrections to many processes

have been calculated. The experimental measurement accuracy has become very precise and now allows comparisons to expectation that are sensitive to higher order and new physics corrections. The current measurements of electroweak processes at LEP/SLD, the top and W boson mass at CDF/D0, and precision charged lepton and neutrino experiments have led to strong constraints on the standard model including the prediction of a light Higgs boson and possibly supersymmetry.

The weak neutral current couplings are parameterized in the SM by a single parameter, the weak mixing angle, $\sin^2 \theta_W$. This mixing angle sets the scale of the left and right-handed couplings of the quarks and leptons to the Z boson. In the SM, the neutrinos are special being that they are neutral particles with only left handed couplings. In addition, neutrinos are now known to have mixing among flavors and also possibly to sterile partners that have no standard model couplings.

Current measurements of many processes show spectacular agreement with the SM.[1] On the other hand, there a few areas that indicate some inconsistencies. The quark and lepton measurements at LEP/SLD show a disagreement at about the three standard deviation level between the b quark forward-back asymmetry and the electron left-right asymmetry. Leptonic measurements tend to predict a light Higgs mass whereas the quark asymmetries would indicate a much heavier Higgs. In addition, the measurement of the invisible width at LEP gives a number of active neutrinos which is too small by about two standard deviations, $N_\nu = 2.985 \pm 0.008$. This may indicate a reduced coupling of neutrinos to the Z boson similar to what would be extracted from the NuTeV measurement described in this manuscript.

Neutrino electroweak measurements are complementary to the collider measurements in that they give better constraints on the neutrino couplings and in probing the theory at low Q^2 . Neutrino-electron scattering ($\nu + e^- \rightarrow \nu + e^-$) provides a very clean probe, but the small cross sections make precision measurements difficult. The Charm II measurements[2] of $(\bar{\nu}_\mu e^-)$ elastic scattering yielded a measurement of $\sin^2 \theta_W = 0.2324 \pm 0.0083$ and $g_V = -0.035 \pm 0.017$ ($SM : -0.0398$) and $g_A = 0.503 \pm 0.017$ ($SM : -0.5065$). Elastic $(\bar{\nu}_e e^-)$ scattering measurements have also been used to probe for a neutrino magnetic moment. Current limits from reactor (accelerator) measurements are $\mu_\nu < 1 \times 10^{-10} \mu_B$ ($6.8 \times 10^{-10} \mu_B$) at 90% CL for electron (muon) neutrinos respectively. SM predictions for magnetic moments give $\mu_\nu = 3.2 \times 10^{-10} \mu_B \times m_\nu / eV$.

Neutrino-quark (nucleon) scattering, on the other hand, provides a process with high statistics at moderate Q^2 but with complications due to

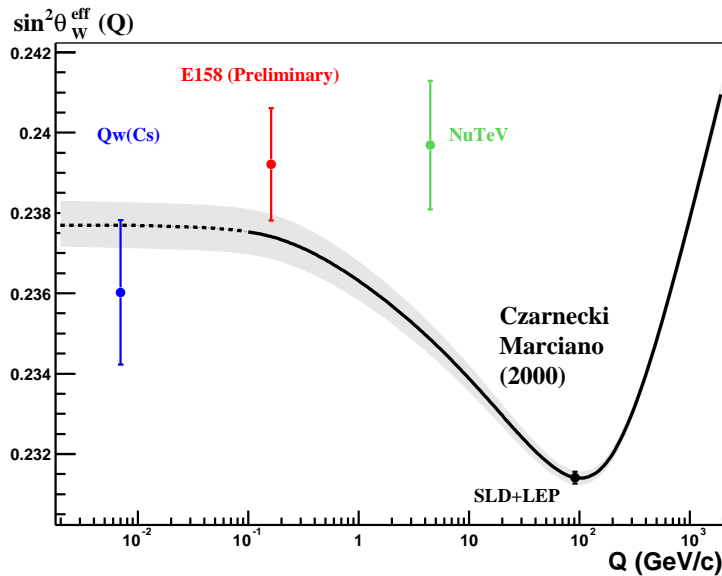


Figure 1: Various electroweak measurements converted to an effective $\sin^2 \theta_W^{eff}$ appropriate for the Moller scattering. The curve is fixed by the precision LEP/SLD measurements at the Z-pole. (From reference [4].)

the quark distribution modeling. Examples here include elastic ($\nu_\mu + p \rightarrow \nu_\mu + p$)[3] and deep-inelastic scattering ($\nu_\mu + N \rightarrow \nu_\mu + X$). Even though they are not sensitive to the neutrino couplings, parity-violating measurements using charged leptons also probe the electroweak model at low Q^2 and have provided several precision results[4] for comparison, as shown in Figure 1.

2 Neutrino Electroweak Measurements Using DIS Scattering

The NuTeV experiment uses neutrino deep-inelastic scattering studies of both muon neutrinos and antineutrinos to make a precision determination of the weak mixing angle. The measurement is the most precise in the neutrino sector and is complementary to others in probing different radiative corrections and physics off the Z pole as well as investigating the coupling of neutrinos and light (u,d) quarks.

In determining $\sin^2 \theta_W$, past neutrino measurements have used the neutral to charged-current ratio in order to cancel many of the systematics associ-

ated with neutrino flux and quark distribution modeling. The neutral-current (NC) to charged-current (CC) cross section ratios for neutrinos and antineutrinos in terms of the $\sin^2 \theta_W$ and ρ is given by

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}} \right) \right). \quad (1)$$

Before NuTeV, this technique was limited in precision due to the systematic uncertainties associated with modeling the corrections to Eq. 1 due mainly to CC charm production from the strange-sea quarks which contributes to the denominator and not the numerator.

For NuTeV, which uses a combination of neutrino and antineutrino measurements, this systematic limitation has been dramatically reduced. This technique was first proposed by Paschos and Wolfenstein[5] and exploits NC and CC cross section differences to reduce the dependence on sea quark contributions. $\bar{\nu}$

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\frac{1}{2} + \sin^2 \theta_W \right) = g_L^2 - g_R^2 \quad (2)$$

where $g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$.

For sea quarks one expects that the quark and antiquark distributions will be identical. Since $\sigma(\nu q) = \sigma(\bar{\nu} \bar{q})$, this means that all sea quark contributions to R^- will be zero at leading order. Specifically under these assumptions, the charm and strange sea error will become negligible and the problematic CC charm production will only have contributions from the fairly well-known valence d quark distributions. The significant improvement in sensitivity is shown in Figure 2, where the NuTeV measurement is compared to other previous neutrino determinations.

3 The NuTeV Neutrino Experiment

In order to exploit the technique of Eq. 2, an experiment must be able to collect separate data sets for neutrino and antineutrino beams. Before NuTeV, separated beams at high energy and high intensity were not available. To accomplish this separation, the NuTeV collaboration developed a new type of sign-selected, quadrupole focused beam. The beam used the 800 GeV protons from the Fermilab Tevatron impinging on a BeO target to produce secondary pions and kaons. Dipole magnets downstream of the target directed mesons of appropriate sign into a quadrupole focusing channel that sent the secondary beam into a 300 m evacuated decay region. The sign

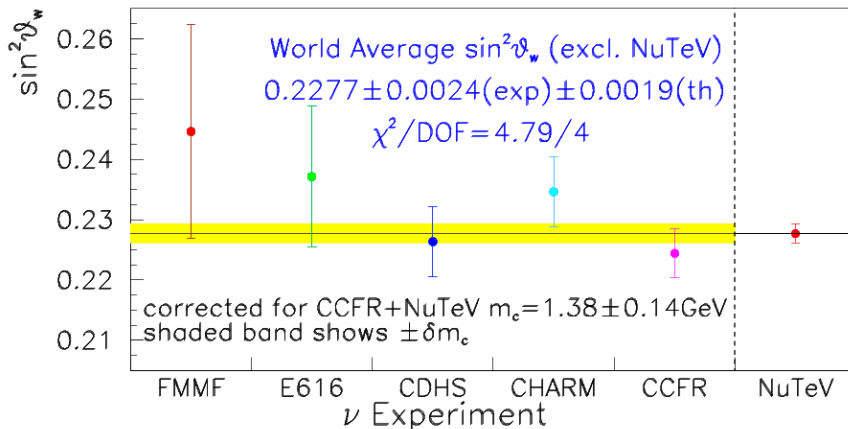


Figure 2: Comparison of the NuTeV $\sin^2 \theta_W$ measurement with those from previous neutrino experiments. All the values have been corrected assuming a charm quark mass of $m_c = 1.38 \pm 0.014$ GeV; the shaded band represents the NuTeV value with the m_c uncertainty.

selection allowed separate ν and $\bar{\nu}$ running, and also removed K^0 mesons that in the past had been a prime source of uncertainty in the electron neutrino contamination. With this design, NuTeV was able to reduce the wrong-sign contamination in the beam to the level of 3×10^{-4} (4×10^{-4}) for neutrino (antineutrino) running while keeping the electron neutrino background to about 1.6%.

Neutrino interactions were observed in the NuTeV detector[6] located approximately 1.5 km downstream of the proton target. The detector consisted of an 18 m long, 690 ton steel-scintillator target followed by an instrumented iron-toroid spectrometer. The target calorimeter was composed of 168 3 m x 3 m x 5.1 cm steel plates interspersed with liquid scintillation counters and drift chambers. The scintillation counters provided triggering information as well as a determination of the longitudinal event vertex, event length, and visible energy deposition. The mean position of the hits in the drift chambers gave the position of the event vertex. The muon spectrometer measured the momentum and charge of final state muons, which was needed in order to determine the neutrino flux as a function of energy. A tagged muon, hadron, and electron calibration beam was used to continuously monitor and study the detector.

Neutrino events in the detector have a hadronic shower component from the struck quark, and for CC events, an outgoing muon. For inclusion in

Source	$\delta R_{\text{exp}}^\nu$	$\delta R_{\text{exp}}^{\bar{\nu}}$
Short CC Background	-0.068	-0.026
Electron Neutrinos	-0.021	-0.024
EM Radiative Corrections	+0.007	+0.011
Charm Mass	-0.005	-0.012
Cosmic-ray Background	-0.004	-0.019
Statistical Error	± 0.0013	± 0.0027

Table 1: Five largest corrections in the determination of $R^{\nu(\bar{\nu})}$ from $R_{\text{exp}}^{\nu(\bar{\nu})}$

the analysis, events were required to have 20 GeV of visible energy in the calorimeter and to satisfy fiducial volume requirements cutting events near detector edges. The observed events were separated into NC and CC statistically based on the ‘‘event length,’’ which was defined in terms of the number of scintillation counters associated with the event. CC events tend to be much longer than NC events due to the outgoing penetrating muon. From test beam and Monte Carlo studies, the separation length was set at 16 to 18 counters depending on the visible calorimeter energy. Using this procedure yielded 457,000 (101,000) short events and 1,166,000 (250,000) long events for the neutrino (antineutrino) data and gave uncorrected ratios of short to long events with statistical errors of

$$R_{\text{exp}}^\nu = 0.3916 \pm 0.0007 \text{ (stat.) and } R_{\text{exp}}^{\bar{\nu}} = 0.4050 \pm 0.0016 \text{ (stat.)}.$$

These experimental ratios can then be related to the physics parameters, $R^{\nu(\bar{\nu})}$ and $\sin^2 \theta_W$, using a detailed Monte Carlo (MC) that includes the physics and detector model. Example effects that need to be included in the MC are: a model of the quark distributions; neutrino fluxes as a function of position and energy; hadronic shower modeling; and detector response versus energy, position, and time. The five largest corrections associated with determining the corrected $R^{\nu(\bar{\nu})}$ values from the measured $R_{\text{exp}}^{\nu(\bar{\nu})}$ ratios are given in Table 1.

With the Monte Carlo tuned to incorporate all the corrections and dependences, one can then do a simultaneous fit to R_{exp}^ν and $R_{\text{exp}}^{\bar{\nu}}$ with an additional constraint on the slow-rescaling mass for charm production (m_c) from the NuTeV $\mu^+\mu^-$ data[7]. This procedure is similar to using an explicit R^- calculation in reducing the uncertainties related to sea quark scattering as well as many experimental systematics common to the ν and $\bar{\nu}$ samples. Statistical and systematic uncertainties in the $\sin^2 \theta_W$ as well as $R^{\nu(\bar{\nu})}$ are shown in Table 2. The final result[8] for the weak mixing angle is

$$\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.),$$

with the error being dominated by statistics. This result is more than a factor of two more precise than the previous world average for νN scattering of $\sin^2 \theta_W = 0.2277 \pm 0.0036$. Comparing to the expectation predicted from the combination of the other electroweak results[1], $\sin^2 \theta_W = 0.2227 \pm 0.0004$, the NuTeV differs by about three standard deviations.

This discrepancy is mainly associated with a 2.6σ difference in the R^ν value since the $R^{\bar{\nu}}$ value is in agreement when systematic errors are also included. The agreement of the $R^{\bar{\nu}}$ value is important since this quantity is most sensitive to systematic uncertainties such as m_c and has reduced sensitivity to $\sin^2 \theta_W$:

$$\begin{aligned} R_{\text{exp}}^\nu &= 0.3916 \pm 0.0013 \quad (SM : 0.3950) \\ R_{\text{exp}}^{\bar{\nu}} &= 0.4050 \pm 0.0027 \quad (SM : 0.4066). \end{aligned}$$

In terms of chiral couplings, the difference with the SM is mainly in the left-handed $g_L^2 = u_L^2 + d_L^2$ coupling:

$$\begin{aligned} g_L^2 &= u_L^2 + d_L^2 = 0.3000 \pm 0.0014 \quad (SM : 0.3042) \\ g_R^2 &= u_R^2 + d_R^2 = 0.0308 \pm 0.0011 \quad (SM : 0.0301). \end{aligned}$$

Global electroweak fits to all measurements including the NuTeV result give a $\chi^2/dof = 25/15$ which has a probability of about 4%. This high χ^2 value has a substantial contribution due to NuTeV but also reflects the tension between the heavy quark and lepton asymmetries.

4 Interpretations of the NuTeV Result

Many interpretations of the NuTeV result have been put forward, spanning areas associated with changes in the standard model fits, changes in standard physics assumptions about quark asymmetries and nuclear effects, and inclusion of physics beyond the standard model. Each of these ideas has been investigated by NuTeV and others with the goal of determining how big a change to the measurement could be accommodated. These investigations are non-trivial, because the NuTeV analysis is complicated, and many of the model assumptions are directly tied to fits and constraints from data. In addition, the measured short-to-long ratio needs to be tied to NC and CC cross sections. Therefore, accurately estimating how much a given change will modify the NuTeV result requires implementing the change into an analysis using these data constraints.

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$	δR^ν	$\delta R^{\bar{\nu}}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \bar{\nu}_e$ Flux	0.00039	0.00025	0.00044
Energy Measurement	0.00018	0.00015	0.00024
Showar Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Interaction Vertex	0.00030	0.00022	0.00017
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, Strange Sea	0.00047	0.00089	0.00184
Charm Sea	0.00010	0.00005	0.00004
$\sigma^{\bar{\nu}}/\sigma^\nu$	0.00022	0.00007	0.00026
Radiative Corrections	0.00011	0.00005	0.00006
Non-Isoscalar Target	0.00005	0.00004	0.00004
Higher Twist	0.00014	0.00012	0.00013
R_L	0.00032	0.00045	0.00101
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272

Table 2: Uncertainties for both the single parameter $\sin^2 \theta_W$ fit and for the comparison of R^ν and $R^{\bar{\nu}}$ with model predictions.

4.1 Changes to Assumptions in the Standard Model Fits

The NuTeV analysis uses an enhanced leading-order formalism that implements constraints from both the observed CC single muon and dimuon data. External measurements are used to parameterize the longitudinal structure function, R_{long} , the d to u quark ratio, the charm quark sea, and higher twist effects (see Ref. [8] for details). Next-to-leading order (NLO) estimates from idealized analyses give small changes in the extracted $\sin^2 \theta_W$ value, $\delta \sin^2 \theta_W = 0.0004$ to $+0.0015$, and quark distribution variations are not sizeable for these idealized analyses[10]. To test possible NLO effects, NuTeV and others are developing full NLO ν event generators that include full NLO evolution with gluon terms and heavy charm effects. Initial indications are that these full calculations will not lead to significant changes[12].

Questions have also been raised with respect to the radiative corrections applied to the data. Although one cannot rigorously break out separate contributions, the largest corrections to the neutral to charged-current ratio come from electromagnetic radiative corrections. Those associated with bremsstrahlung from the final state muon in charged current events are especially large but are straightforward to calculate. NuTeV uses the only currently available code from Bardin and Dokuchaeva[13] which when applied shifts the result by $\delta \sin^2 \theta_W = -0.008$. New calculations are now becoming available that have improved treatment of the initial state mass singularities and allow investigations of input parameters and scheme dependence[14]. NuTeV plans to implement these new codes into the analysis to quantitatively determine their impact.

4.2 Changes in Standard Physics Assumptions

The Paschos-Wolfenstein relation in Eq. 2 assumes isospin symmetry, $u_p(x) = d_n(x)$ and $d_p(x) = u_n(x)$, assumes momentum symmetry for the sea quarks, $xs(x) = x\bar{s}(x)$ and $xc(x) = x\bar{c}(x)$, and assumes that any nuclear environment effects are common for both W and Z boson exchange. Violations of these symmetries are possible but subject to constraints from various measurements. The NuTeV collaboration has investigated many of these effects and has provided a weighting function that can be convoluted with a given model to provide the shift that would result for the extracted $\sin^2 \theta_W$ value[9].

Isospin symmetry violations could come from quark mass effects ($m_u \neq m_d$) or wave function differences due to the different quark charges. To explain the NuTeV discrepancy would require d_V quarks in the proton to carry about 5% more momentum than the u_V quarks in the neutron. Models

of these effects are not very predictive but typically predict values less than about 1.5% [15], [9]. As stated by several authors, making conclusions from phenomenological models is difficult and new data will be needed in order to constrain possible isospin violation effects to the $\sin^2 \theta_W$ measurement.

A strange-antistrange quark momentum asymmetry ($xs(x) = x\bar{s}(x)$) in the nucleon has also been put forward as a possible explanation for the NuTeV discrepancy [16]. The NuTeV dimuon results provide a direct measure of this asymmetry through the processes

$$\begin{aligned} \nu + s &\rightarrow \mu^- + c \rightarrow \mu^- \mu^+ + X \\ \bar{\nu} + \bar{s} &\rightarrow \mu^+ + \bar{c} \rightarrow \mu^+ \mu^- + X. \end{aligned}$$

NuTeV has performed a full NLO analysis of the dimuon data [11] and has restricted the strange sea asymmetry to

$$\int xs^-(x)dx = \int \frac{1}{2} (xs(x) - x\bar{s}(x)) dx = -0.0009 \pm 0.0014.$$

A value for this integral of +0.0060 would be needed to explain the NuTeV discrepancy which would be inconsistent with this measurement.

Nuclear effects that are different for W and Z boson exchange could be important for the NuTeV analysis. Most nuclear effects are only large at small Q^2 and would affect W and Z exchange the same. NuTeV is at relatively high Q^2 with mean values of 25 (16) GeV^2 for ν ($\bar{\nu}$) events, and the NuTeV $\sin^2 \theta_W$ extraction shows no effect with increasing the visible hadron energy cut. In addition, the quark distribution measurements show no $1/Q^2$ dependence in the NuTeV kinematic region. Enhanced vector dominance models have been proposed but mainly affect sea quarks at low x and would cancel in R^- [9]. Furthermore, these nuclear corrections would change R^ν and R^ν more than R^- making their deviation with the SM even larger.

4.3 Physics Beyond the Standard Model

The NuTeV discrepancy could be related to anomalous neutrino properties. Interpreting the NuTeV data in terms of a reduced neutral current coupling ρ_0 , by fixing $\sin^2 \theta_W$ to its SM value, yields a value of

$$\rho_0^2 = 0.9884 \pm 0.0026(\text{stat.}) \pm 0.0032(\text{syst.})$$

which is a 2.8 σ deviation from expectation. This is consistent with the LEP determination of the invisible width ("neutrino counting") result which is also 1.9 σ low. Thus, these results could be explained by invoking a lower

effective coupling of neutrinos due to some new phenomena (*i.e.* mixing with heavy or sterile neutrinos). Giunti[17] has also speculated that neutrino oscillations of electron to sterile neutrinos could make the intrinsic electron neutrino background in NuTeV smaller, leading to a smaller measured value for $\sin^2 \theta_W$. This simple model would require a level of 20% mixing and a high Δm^2 which is inconsistent with current limits. J.S. Ma *et al.* have recently made further investigations, and shown that models with several sterile neutrinos (3+2 models) when constrained by existing limits can at most explain 0.3σ of the NuTeV discrepancy with the SM[18].

Other possible new physics interpretations have also been considered. These interpretations need to respect the constraints from the precision Z-pole measurements from LEP and SLD. But, to a large extent, these constraints are insensitive to effects not directly involving the Z and are not too constraining with respect to neutrino couplings. In explaining the NuTeV measurements, these new physics models have to provide a change in R^ν (or g_L) without changing $R^{\bar{\nu}}$ (or g_R). One possibility is SUSY particle contributions to loop corrections or R-parity violating SUSY corrections at tree level. Studies of these possibilities show that the effects are generally small and in the wrong direction. In addition, it is almost universal that these corrections change both R^ν and $R^{\bar{\nu}}$ at a similar level. It may be possible in extended SUSY models to produce an ν to $\bar{\nu}$ asymmetry in the corrections and several authors have pursued such models[19].

Considering other types of models, a finely tuned contact interaction where an additional left-handed, quark-lepton vertex interaction is added with a strength of 1% of the weak interaction (giving a scale of about 5 TeV) could explain the NuTeV result. Imposing leptoquarks to explain the effect is generally difficult, since these corrections would increase both the NC and CC rate making the g_L discrepancy larger and tend to violate constraints from π -decay. Finally, one can introduce extra U(1) vector bosons that are tuned to have special reduced couplings to 2nd generation leptons. In all of these cases, one will have to wait for the results from searches at the Tevatron and LHC to see if any of these possibilities might be viable.

Several authors have considered combination models to explain the NuTeV result. Typically, one invokes special neutrino properties combined with changes to standard model parameters and possibly new particles. Loinza *et al.*[20] have suggested a model which has neutrino mixing, a heavy Higgs-boson mass, and new heavy bound states. The $Z\nu\nu$ coupling is suppressed by having flavor dependent mixing of the standard neutrinos with new heavy, sterile neutrinos. This suppression leads to many inconsistencies with the Z-pole measurements that are corrected by invoking a Higgs mass greater than 200 GeV. The heavy Higgs mass is inconsistent with the measurements of

the W boson mass; these are then accommodated by including new physics associated with new heavy bound states (U-parameter type new physics). For fits where the neutrino coupling has a flavor independent suppression, the models yield a reduction in the $Z\nu\nu$ coupling of $(1 - \varepsilon) = 0.003 \pm 0.001$. Allowing for flavor dependent corrections gives better overall fits with, for example, $(1 - \varepsilon) = 0.005 \pm 0.002, 0.003 \pm 0.001$, and 0.001 ± 0.003 for e, μ , and τ suppressions respectively.

5 Future Measurements

As outlined above, there are uncertainties in both the experimental and theoretical situation that will require new measurements for clarification. In particular measurements are needed at low Q^2 as well as for processes involving neutrinos. New information on charged lepton scattering at low Q^2 is becoming available both now and in the near future. The SLAC E158 experiment has put out preliminary results[4] ($\sin^2 \theta_W(M_Z) = 0.2330 \pm 0.0011$ (stat.) ± 0.0010 (syst.) ± 0.0006 (theory)) for their full data set which shows a $+1.2 \sigma$ discrepancy from the SM prediction as shown in Fig. 1. Electroweak measurements at JLab include the QWEAK experiment (<http://www.jlab.org/qweak/>) which will measure polarization asymmetries for electron-proton elastic scattering and the DIS-Parity experiment (<http://www.jlab.org/~xiaochao/pac24/>) which will make study polarized electron-deuteron scattering. Both experiments should have good precision with similar or better uncertainties than the E158 measurements.

In the neutrino sector, the Nomad experiment is attempting to measure the weak mixing angle using their large statistical sample of neutrino only data. The idea is to apply next-to-next-to-leading-order and $1/Q^2$ corrections to account for quark model effects, as well as use dimuon data to constrain the strange and the charm mass. Initial sensitivity estimates have been presented[21] giving errors of $\delta \sin^2 \theta_W = 0.002$ (stat.) ± 0.003 (syst.).

Other possible precision electroweak measurements include neutrino-electron scattering, which would eliminate any QCD and quark model corrections. The CHARM II result[2] is presently the most precise for $\nu_\mu e$ scattering but suffers from poor statistics due to the very small cross section. An improved experiment with $\times 25$ better statistics could reach the level of $\delta \sin^2 \theta_W = 0.002$ but would require a very large (~ 5000 tons), fine-grained detector such as a liquid argon TPC combined with a high energy neutrino beam that has a rate an order of magnitude greater than NuTeV.

Recently, Conrad *et al.*[22] have suggested that electron antineutrinos from a reactor might be used to measure $\bar{\nu}_e e^-$ elastic scattering. The process

is a combination of W and Z exchange with the total rate being sensitive to $\sin^2 \theta_W$. The reactor provides a very high rate of neutrinos, and when combined with a modest sized (~ 50 ton) detector can give sensitivities at the $\delta \sin^2 \theta_W = 0.002$ level. Such an experiment could be realized as part of a two detector $\bar{\nu}_e$ disappearance search for neutrino oscillation. The near detector would be used for the weak mixing angle measurement as well as providing the event normalization for the oscillation search in the far detector. In the near detector, the CC inverse beta-decay process ($\bar{\nu}_e + p \rightarrow e^- + n$) would provide the event normalization for the elastic scattering measurement and the far detector would monitor backgrounds. Using these techniques, the measurement would provide a clean, purely leptonic electroweak measurement using neutrinos and would be complementary in addressing the NuTeV discrepancy[23].

In summary, the NuTeV measurement has the precision to be important for tests of the standard model and the experimental technique and cross checks are robust with respect to systematic uncertainties. In comparison with prediction, the extracted $\sin^2 \theta_W$ is about three sigma high indicating a lower effective coupling to left-handed quarks or a neutral current coupling that is $\sim 1.1\%$ smaller than expected. Interpretations have spanned the range from uncertainties in the quark and other model corrections to possible new physics associated with neutrinos and their interactions or mixings. Future measurements will be needed to explore the NuTeV measurement and its possible explanations.

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