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UPDATED ELECTROWEAK MEASUREMENTS FROM NEUTRINO-NUCLEON DEEPLY INELASTIC SCATTERING AT CCFR

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Talk Presented by K. S. McFarland

Abstract

We report the results of a study of electroweak parameters from observations of neutral-current νN deeply inelastic scattering in the CCFR detector at the FNAL Tevatron Quadrupole Triplet neutrino beam. An improved extraction of the weak mixing angle in the on-shell renormalization scheme, incorporating additional data and with an improved technique for constraining systematic errors, is presented. Within the Standard Model, this result constrains the W mass with a precision comparable to that from direct measurements. The result is also presented in a model-independent form, as constraints on neutral-current quark-neutrino couplings, to facilitate comparisons with theories outside the Standard Model. Using this result, limits on new four-fermion interactions, leptoquarks and neutrino oscillations are presented. Prospects for a successor experiment, NuTeV (FNAL-E815), are also presented.

1 Introduction

In neutrino-nucleon (νN) scattering, the ratio of neutral current (Z exchange) to charged current (W exchange) cross-sections is related to the neutral current quark couplings by the Llewellyn-Smith formula [1]:

$$R^{\nu} \equiv \frac{\sigma(\nu_{\mu}N \rightarrow \nu_{\mu}X)}{\sigma(\nu_{\mu}N \rightarrow \mu^{-}X)} \quad (1)$$

$$= (g_L^2 + r g_R^2), \quad (2)$$

where

$$r \equiv \frac{\sigma(\overline{\nu}_{\mu}N \rightarrow \mu^{+}X)}{\sigma(\nu_{\mu}N \rightarrow \mu^{-}X)}, \quad (3)$$

and $g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$, the isoscalar sum of the squared left or right-handed quark couplings. There are small corrections to this relation from higher-twist effects, isovector components to the nuclear target and electromagnetic radiative effects, and a substantial correction from massive quark effects, such as scattering from the strange or charm sea. Because the neutral current quark couplings are functions of the weak mixing angle, θ_W, a measurement of R^{ν} can be used to extract $\sin^2\theta_W$.

Electroweak radiative corrections introduce significant M_{top} and M_{Higgs} dependences into these couplings. However, in the "on-shell" (Sirlin) Renormalization scheme where $\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$, the one-loop electroweak radiative corrections to the quark couplings cancel approximately in equation 2 [2]. Therefore, if the quantity R^{ν} is measured and used to extract a value of $\sin^2\theta_W$, the result will be almost equal to $1 - \frac{M_W^2}{M_Z^2}$. Given the very precise measurement of the Z mass from the LEP experiments, νN scattering can, within the Standard Model, provide a precise measurement of M_W at energies far below W production threshold.

Outside the Standard Model, deviations between electroweak parameters measured in νN scattering and other processes are sensitive to a host of new physics possibilities [3]. Possibilities discussed in this paper include new four-fermion contact interactions at high mass scales, leptoquarks and neutrino oscillations. Discussed elsewhere in these proceedings is the possibility that νN scattering may be sensitive to "leptophobic" Z' bosons [4][5].

2 Experimental Technique

The CCFR detector consists of an 18 m long, 690 ton target calorimeter with a mean density of 4.2 g/cm^3, followed by an iron toroid spectrometer. The target calorimeter consists of 168 iron plates, 3m $\times$ 3m $\times$ 5.1cm each. The active elements are liquid scintillation counters spaced every two plates and drift chambers spaced every four plates. There are a total of 84 scintillation counters and 42 drift chambers in the target. The toroid spectrometer is not directly used in this analysis.

The Tevatron Quadrupole Triplet neutrino beam is created by decays of pions and kaons produced when 800 GeV protons hit a production target. A wide band of secondary energies is accepted by focusing magnets. The production target is located about 1.4 km upstream of the neutrino detector. The production target and focusing train are followed by a 0.5 km decay region. The beam is predominantly muon neutrinos and anti-neutrinos, but contains a small fraction of electron neutrinos (2.3%) and a negligible fraction of tau neutrinos (less than 10^{-5}) which result primarily from D_s decay.

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$
data statistics	**0.0021**
Monte Carlo statistics	0.0005
TOTAL STATISTICS	0.0021
Charm Production	
($m_c = 1.31 \pm 0.24$ GeV)	**0.0029**
Charm Sea	**0.0014**
Longitudinal Cross-Section	0.0008
Higher Twist	0.0005
Non-Isoscalar Target	0.0003
Strange Sea	0.0003
Structure Functions	0.0002
Rad. Corrections	0.0001
TOTAL PHYSICS MODEL	0.0034

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$
ν_e flux (4.2%)	**0.0022**
Transverse Vertex	0.0008
Energy Measurement	
Muon Energy Loss in Shower	0.0006
Absolute Energy Scale (1%)	0.0004
Hadron Energy Scale (0.6%)	0.0002
Event Length	
Hadron Shower Length	0.0006
Vertex Determination	0.0008
Counter Efficiency and Noise	0.0006
Dimuon Production	0.0003
TOTAL EXP. SYST.	0.0027
TOTAL UNCERTAINTY	0.0048

Table 1: Uncertainties in the *preliminary* extraction of $\sin^2 \theta_W$ from the CCFR data

Neutrinos are observed in the target calorimeter *via* their neutral current and charged current interactions. ν_μ charged current events are characterized by the presence of a muon in the final state which deposits energy in a large number of consecutive scintillation counters as it travels through the calorimeter. Neutral current events have no muon and deposit energy over a range of counters typical of a hadronic shower (5 to 20 counters). Accordingly, we define "short" events as those which deposit energy over an interval of 30 or fewer scintillation counters. The ratio R_{30} is defined to be the number of short events divided by the number of long events [6].

We define E_{cal} as the energy deposited in the calorimeter in the first twenty counters following the event vertex. Events were selected using a calorimeter trigger fully sensitive for E_{cal} above 20 GeV, and only events with E_{cal} above 30 GeV were used in the analysis. To ensure event containment, the fiducial volume of the detector is limited to a central cylindrical region 30" in radius and excludes events which began in the first 6 counters or the last 34 counters of the detector. The resulting data sample consisted of about 660,000 events.

A detailed Monte Carlo was used to determine electroweak parameters from the measured R_{30}. The only undetermined inputs to this Monte Carlo were the neutral current quark couplings which were then varied until the Monte Carlo predicted an R_{30} which agreed with that observed in the data. For the extraction of $\sin^2 \theta_W$, the couplings in the Monte Carlo were fixed to their Standard Model predictions as functions of $\sin^2 \theta_W$ which was then varied as the only free parameter. The Monte Carlo included detector response and beam simulations, as well as a detailed cross-section model which included electromagnetic radiative corrections, isovector target corrections, heavy quark production and seas, the longitudinal cross-section and lepton mass effects.

There are three major uncertainties in the comparison of R_{30} from the Monte Carlo to the data: the statistical error in the data, the uncertainty in the effective charm quark mass for charged current charm production, the uncertainty in the incident flux of ν_e's on the detector. Other sources of systematic uncertainty were also investigated [6]. Table 1 shows the effect of the uncertainties on the determination of $\sin^2 \theta_W$.

The charm mass error comes from the uncertainty in modeling the turn-on of the charm quark production cross section. The Monte Carlo uses a slow-rescaling model with the parameters extracted using events with two oppositely charged muons in this experiment [7]. This

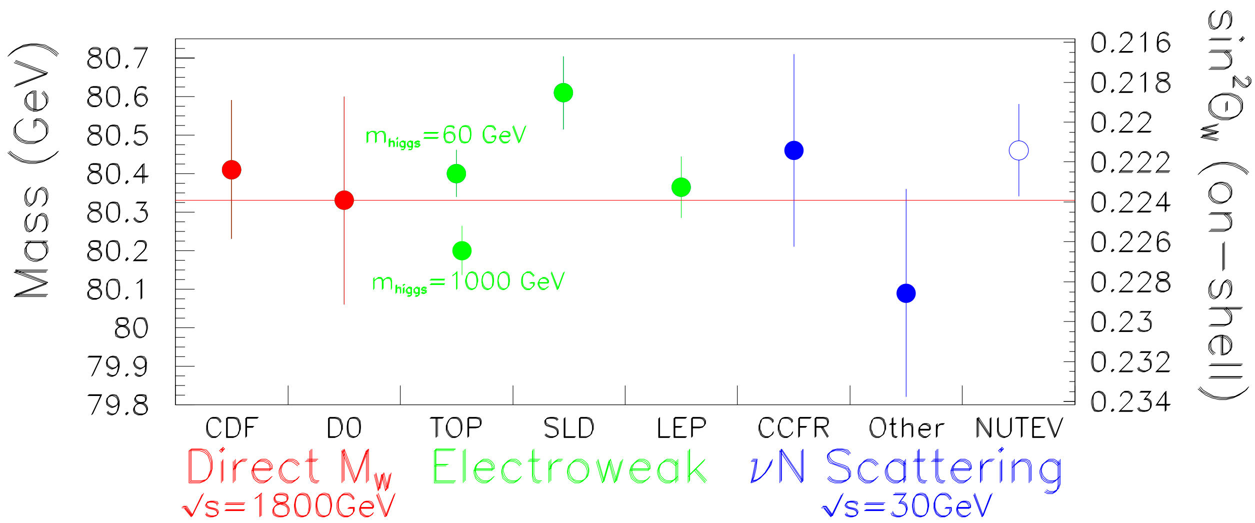

Figure 1: A comparison of different precision electroweak measurements, shown as a predicted W mass within the Standard Model

error dominates the calculation of R_{30} at low E_ν (and low E_{cal}) where the threshold suppression is greatest. The ν_e flux uncertainty has a large effect on R_{30} because almost all charged current ν_e events are short events. Therefore, the relatively small (4.2% [6]) fractional uncertainty in the ν_e flux is a large effect, particularly at high E_{cal} since most ν_e charged current interactions deposit the full incident neutrino energy into the calorimeter. This 4.2% is dominated by a 20% production uncertainty in the K_L content of the secondary beam which produces 16% of the ν_e flux. The bulk of the ν_e flux comes from $K^\pm_{e3}$ decays, which are well-constrained by the observed ν_μ spectrum from $K^\pm_{\mu 2}$ decays [6].

3 Results

CCFR has updated its previously published result [6] with the addition of more data and an improved analysis of systematic errors. The new *preliminary* result from CCFR for the weak mixing angle in the on-shell renormalization scheme is:

$$\sin^2\theta_W = 0.2213 \pm 0.0021(\mathrm{stat}) \pm 0.0027(\mathrm{syst}) \pm 0.0034(\mathrm{model}). \tag{4}$$

The additional uncertainty on this on-shell $\sin^2\theta_W$ from $m_{\mathrm{top}} = 174 \pm 10$ GeV due to the one-loop electroweak radiative corrections is ± 0.0003. Within the Standard Model, this corresponds to a W mass of 80.46 ± 0.25 GeV. It is possible to combine the world's νN scattering data on isoscalar targets and obtain an average. However, because of the large charm production systematic which is common to all experiments, there is not much improvement. Combining the five most precise experiments, $\sin^2\theta_W = 0.2261 \pm 0.0040$, with a χ^2/DOF of 5.33/4. Shown in Figure 1 is the good agreement of equivalent W mass measurements from νN experiments, direct measurements from the Tevatron, and derivations from Z^0 observables and m_{top}.

To facilitate comparisons with extensions to the Standard Model, this result can also be expressed as a model-independent constraint on the neutral-current quark couplings. The *preliminary* CCFR constraint is

$$\kappa = 0.5629 \pm 0.0048 = 1.7266 g_L^2 + 1.1198 g_R^2 - 0.1008 \delta_L^2 - 0.0865 \delta_R^2 \tag{5}$$

where $(\overset{g}{\delta})^2_{L,R} = u^2_{L,R}(\pm) d^2_{L,R}$. The Standard Model prediction is $\kappa = 0.5623 \pm 0.0016$ for the

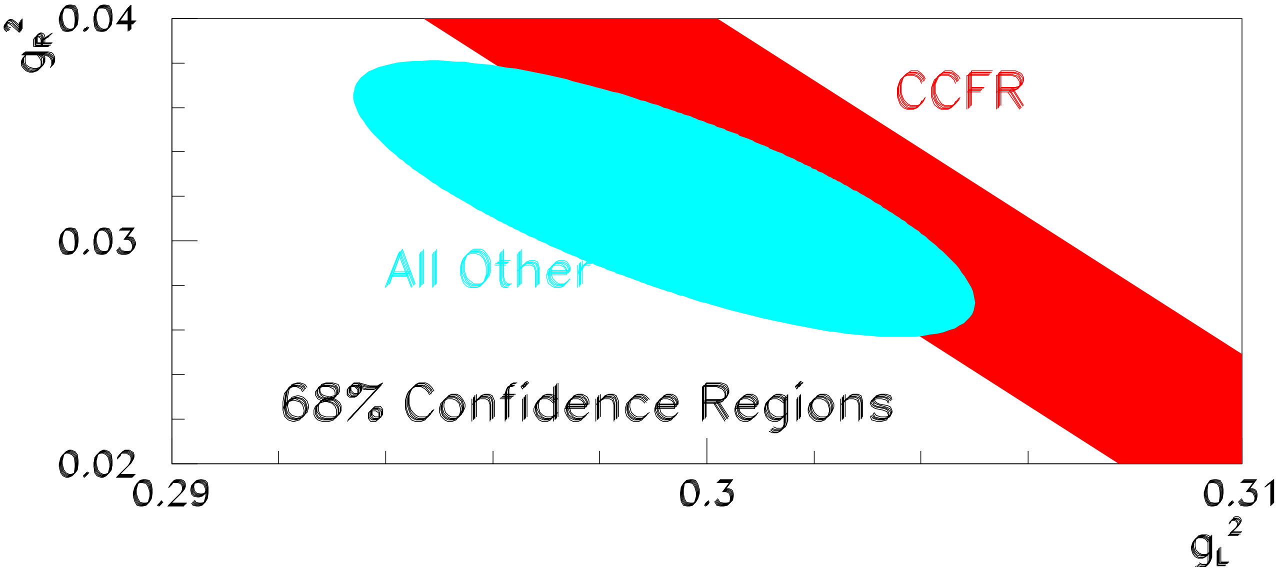

Figure 2: One-sigma constraints on the isoscalar neutral current quark couplings, g_L^2 and g_R^2, from this result and other neutrino data.

measured values of m_Z, $m_{\rm top}$, m_W. Figure 2 shows this result compared with a fit to other neutrino data [8].

4 Constaints on New Physics

The following sections make use of the value of κ given in equation 5 and its Standard Model value to set limits on new physics possibilities.

4.1 Compositeness Scales

One can postulate a four-fermion interaction between two neutrinos and two quarks, and add a term to the interaction Lagrangian of the form $-\mathcal{L} = \pm(4\pi/\lambda_{LL}^{\pm})\bar{l}_{\mu L}\gamma^{\nu}l_{\mu L}\overline{q}_L\gamma_{\nu}q_L$. This interaction will shift the predicted values for the neutral current quark couplings, and thus the νN data can limit the allowed range of $\lambda_{LL}^{\pm}$. From the preliminary CCFR result, at 95% confidence, $\lambda_{LL}^{+} > 3.8$ TeV or $\lambda_{LL}^{-} > 3.5$ TeV.

4.2 Leptoquarks

The model used for this search is an SU(5)-inspired model [3]. If there are no leptoquark-induced flavor-changing neutral currents and if the left-handed coupling of the leptoquark (η_L) is much larger than its right-handed coupling, νN is one of the most sensitive probes. From the preliminary CCFR result, at 95% confidence, $M_L/|\eta_L| > 0.8$ TeV.

4.3 Neutrino Oscillations

Neutrino oscillations, if present, would also affect the measured neutral current quark couplings. This is because charged-current events are selected by the presence of a muon in the final state, and clearly if muon neutrinos oscillate to either electron or tau neutrinos, they are less likely to produce final-state muons in their charged current interactions. Details of this analysis can be found elsewhere [9]; the limits obtained are shown in Figure 3.

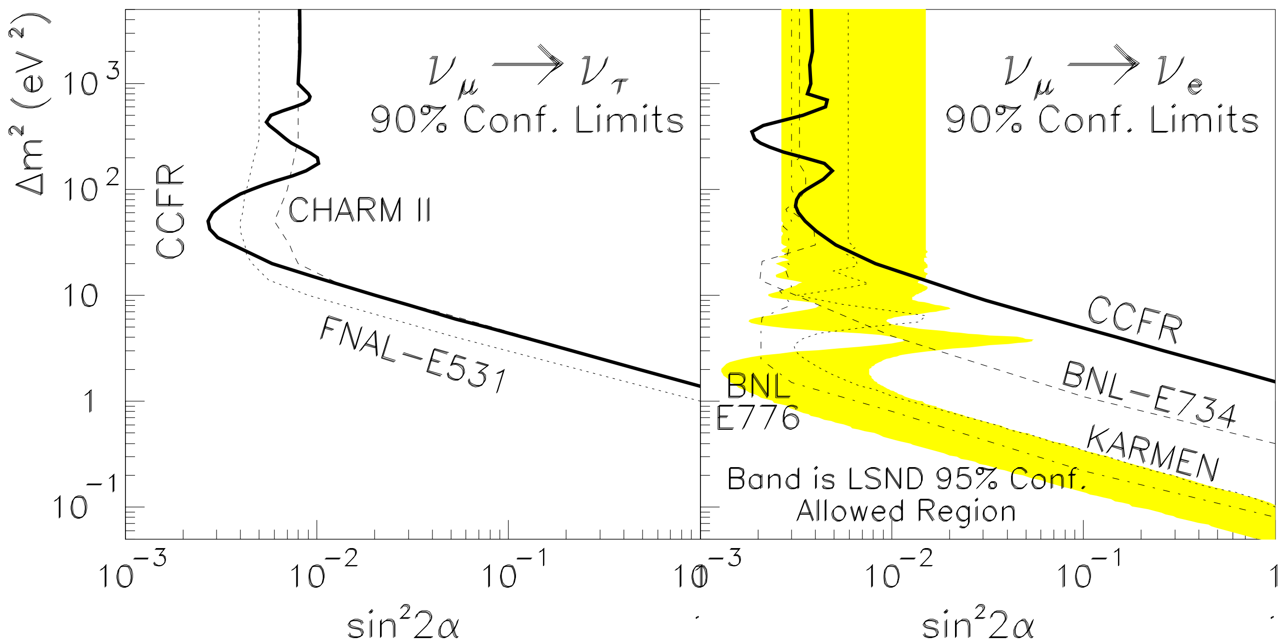

Figure 3: 90% confidence limits on $\nu_\mu \rightarrow \nu_{\tau,e}$ oscillation from the CCFR electroweak measurement compared with othger experiments

5 Conclusions

Even in the era of high-luminosity colliders that produce copious on-shell W and Z bosons, neutrino-nucleon deeply inelastic scattering remains an interesting system in which to pursue measurements of electroweak parameters. Within the Standard Model, the CCFR measurement of $\sin^2\theta_W$ from νN scattering provides a measurement of the W mass with comparable precision to current measurements at the Tevatron. Outside the Standard Model, this measurement is sensitive to new physics at the TeV scale and to neutrino oscillations.

The NuTeV experiment at Fermilab will continue to improve the precision of measurements of νN scattering. A new beamline, the Sign-Selected Quadrupole Train (SSQT), will run from 1996-1998 and provide separate high-intensity neutrino and anti-neutrino beams, This will allow separate measurements of the neutrino and anti-neutrino neutral current cross-sections. The difference, $\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}$, is insensitive to sea quark distributions, and will allow a measurement of $\sin^2\theta_W$ with model errors reduced by a factor of 3. The SSQT also produces almost no electron neutrinos from K_L decays, thus removing the dominant source of experimental uncertainty in the CCFR measurement. NuTeV projects a precision of ± 0.0019 in its measurement of $\sin^2\theta_W$ which corresponds within the Standard Model to a W mass precision of 100 MeV.

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