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RECENT ELECTROWEAK RESULTS FROM $\nu - \mathrm{N}$ SCATTERING AT NUTEV

JAEHOON YU

MS357, FNAL, P.O.Box 500, Batavia, IL 60510, USA

NuTeV is a neutrino-nucleon deep inelastic scattering experiment which took its data in the 1996-97 Fermilab TeVatron 800 GeV fixed target run. We present the results of two recent electroweak analyses in this paper, using this data set. We present a precision measurement of $\sin^2\theta_W$, using the Paschos-Wolfenstein relationship, which minimizes large systematic uncertainties caused by charged current production of charm quarks in the final state. The result of the measurement is $\sin^2\theta_W = 0.2253 \pm 0.0019 \pm 0.0010$. The resulting mass of the W boson is $M_W = 80.26 \pm 0.11\mathrm{GeV/c^2}$ and is comparable to direct measurements from TeVatron and LEP-II. In addition, we present a measurement of the cross section for the inverse muon decay process. The measured cross section is $\sigma_{\mathrm{IMD}}/E_\nu = (14.2 \pm 2.9) \times 10^{-42}\mathrm{cm^2/GeV}$ which is consistent with its Standard Model prediction.

1 Introduction

Neutrino-nucleon deep inelastic scattering is an excellent testing field of the Standard Model (SM), especially the electroweak sector, because neutrinos interact only weakly. Neutrino deep inelastic processes provide a precise measurement of the weak mixing angle, $\sin^2\theta_W$, and, in turn, provide the mass of W boson, M_W, within the context of the Standard Model, at precision comparable to direct measurements.

In addition, in the momentum transfer range of these processes, the $\sin^2\theta_W$ measurement is sensitive to light quark couplings and hence to any anomalies in the quark couplings caused by extra bosons or other non-SM couplings. In other words, this measurement is sensitive to new physics, such as compositeness of quarks or neutrino oscillations. Other electroweak measurements in $\nu - \mathrm{N}$ scattering, such as the inverse muon decay process, also provide additional tools to probe the Standard Model and to look for new physics.

In this paper, we present the results of the $\sin^2\theta_W$ measurement, as well as the recent cross section measurement for the inverse muon decay (IMD) process.

2 Precision Measurement of $\sin^2\theta_W$

The coupling between the light quarks in charged current (CC) interactions of neutrino and nucleon is, to first order, proportional to the weak isospin while the neutral current (NC) interactions are proportional to weak isospin as well as the mixing angle. The mixing angle needs to be introduced to provide probability distributions of the NC events mediated by neutral heavy vector boson and a electromagnetic gauge boson. Therefore, the ratio between CC and NC cross sections is proportional to $\sin^2\theta_W$.

The most important element in this measurement is separating NC from CC events. This separation is obtained statistically by using the event length variable. The event length is defined for each event to be the number of consecutive calorimeter [1] scintillation counters with energy deposition above 1/4 of that of a single muon. NC events have short length due to the absence of muons in the event, while CC events are long. Thus, the experimentally measured ratio $\mathcal{R}_{meas} = N_{short}/N_{long}$, represents the NC to CC cross section ratio, $\mathcal{R}^{\nu(\overline{\nu})}$.

The Monte Carlo (MC) incorporates a leading order (LO) corrected Quark-Parton-Model (QPM), using LO parton distribution functions from the CCFR structure function measurements, together with a detailed detector simulation. The detailed MC also takes into account radiative corrections, target isovector and higher order QCD effects, and heavy quark production.

There are two major sources of systematic uncertainty in the CCFR measurements [2,3]. The first is the theoretical uncertainty due to mass threshold effects in the CC production of charm quarks which results in $\delta\sin^2\theta_W = 0.0027$. The second source is the lack of precise knowledge of the ν_e flux in the beam from neutral kaon decays. The size of this uncertainty is 2.9% uncertainty in N_{ν_e} which results in $\delta\sin^2\theta_W = 0.0015$.

Minimizing the two largest systematic uncertainties requires a technique insensitive to the sea quark distributions and a beamline which minimizes the number of electron neutrinos, especially those resulting from K_L decays. In order to minimize the uncertainty due to the charm quark production, NuTeV uses the Paschos-Wolfenstein parameter [4]:

$$\mathcal{R}^- = \frac{\sigma^\nu_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^\nu_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{R^\nu - rR^{\overline{\nu}}}{1-r} = (g_L^2 - g_R^2) = \rho\left(\frac{1}{2} - \sin^2\theta_W\right). \quad (1)$$

Since $\sigma^{\nu q} = \sigma^{\overline{\nu}\overline{q}}$ and $\sigma^{\overline{\nu} q} = \sigma^{\nu\overline{q}}$, the effect of scattering off the sea quarks cancels by taking the differences in the neutrino and antineutrino cross sections. However, the measurement of this quantity is complicated due to the fact that the NC final states look identical for ν and $\overline{\nu}$. NuTeV built a Sign Selected Quadrupole Train (SSQT) to select either ν or $\overline{\nu}$ beam at a given running period to accomplish discrimination of NC events in the two beams. The uncertainty caused by the ν_e flux is minimized by reducing neutral secondary particle acceptances.

The extraction of $\sin^2\theta_W$ in NuTeV is based on a data sample of 1.3 million neutrino and 0.3 million antineutrino events passing a set of fiducial and energy cuts. The resulting ratios of NC candidates (short length) to CC candidates (long length), $\mathcal{R}^{\nu(\overline{\nu})}_{meas}$, are 0.4198 ± 0.008(stat) and 0.4215 ± 0.0017(stat) for neutrino and antineutrino, respectively. The variable $\mathcal{R}_{meas}$ is then related to $\sin^2\theta_W$, using a detailed MC.

To extract $\sin^2\theta_W$ from these measured ratios, we form a linear combination of $\mathcal{R}^\nu_{meas}$ and $\mathcal{R}^{\overline{\nu}}_{meas}$:

$$\mathcal{R}^-_{meas} \equiv \mathcal{R}^\nu_{meas} - \alpha\mathcal{R}^{\overline{\nu}}_{meas}, \quad (2)$$

where α is determined using the MC such that $\mathcal{R}^-_{meas}$ is insensitive to small changes in the CC cross sections due to the charm mass threshold effect. For this measurement, the value of α is found to be 0.514. This technique essentially employs the third expression in Eq. 1 instead of the second which requires separate background estimates and flux normalizations for neutrino and antineutrino cross sections. This technique cancels out a large number of systematics by taking ratios separately in neutrino and antineutrino modes while at the same time largely canceling the uncertainties related to charm quark production from the sea quark scattering. The remaining small uncertainty due to heavy quark production results from the scattering off the d-valence quark which is Cabbibo suppressed. The dominant uncertainty in this measurement is the data statistics.

The preliminary result from the NuTeV $\sin^2\theta_W$ measurement in the on-shell renormalization scheme is :

$$sin^2\theta_W^{(on-shell)} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst}). \quad (3)$$

The small residual dependence of this result on M_{top} and M_H comes from the leading terms in the electroweak radiative corrections [5]. Within the on-shell renormalization scheme, together with the Standard Model prediction of ρ, the $\sin^2\theta_W$ is related to M_W and M_Z by $\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$, implying:

$$M_W = 80.26 \pm 0.10(\text{stat}) \pm 0.05(\text{syst})$$

$$+0.073 \times \left(\frac{M_{top}^2 - (175GeV)^2}{(100GeV)^2}\right)$$
$$-0.025 \times log_e \left(\frac{M_H}{150GeV}\right). \quad (4)$$

This result is in good agreement with and is in comparable precision to other M_W measurements.

3 Inverse Muon Decay Cross Section Measurement

The inverse muon decay (IMD) process provides a clean test of the weak sector because it is a purely leptonic reaction: $\nu_\mu + e^- \to \mu^- + \nu_e$. Since the process involves only one muon with little deflection, its signature is very distinct. Furthermore, this reaction only occurs in the ν_μ beam, because there are no intrinsic positrons in atoms. Thus any indication of the equivalent reaction in the $\overline{\nu}_\mu$ beam would be due to a lepton number violating (LNV) reaction with $\Delta\mathcal{L} = 2$: $\overline{\nu}_\mu + e^- \to \mu^- + \overline{\nu}_e$. The IMD process also provides the tools for estimating the background contributions to LNV ($\Delta\mathcal{L} = 2$) processes in anti-neutrino mode. The Standard Model prediction of the cross section for this process in the limit of $s \gg m_\mu^2$:

$$\sigma(\nu_\mu + e^- \to \mu^- + \nu_e) = G_F^2 s/\pi$$
$$= 17.2 \times 10^{-42} \mathrm{E}_\nu \mathrm{cm}^2. \quad (5)$$

The candidate event are required to satisfy the following cuts: 1) the event must be within the fiducial volume, 2) the μ^- must be well measured and fully contained in neutrino running mode, 3) the hadronic energy must be less than 3 GeV, and 4) the transverse momentum of muons, p_T^μ, must be lower than P_T^{Max} where $P_T^{Max} = 0.059 + E_\mu/671.1$ GeV/c, which is designed to retain 95% of IMD events. The overall cut efficiency is found to be approximately 81%.

The background taken into account for this measurement are quasi-elastic scattering ($\nu_\mu + n \to \mu^- + p$), resonance production ($\nu_\mu + N \to \mu^- + R$), and coherent meson production off the nucleus. All of these processes are expected to be produced equally by high energy neutrinos and antineutrinos. Therefore, the background from these processes can be estimated from the antineutrino data.

We employ two different methods for the background subtraction. The first is a direct subtraction method which uses events with low hadronic energy in antineutrino mode. This method is limited by statistics in antineutrino mode. We have also developed a Monte Carlo based method which is, at the moment, dominated by various modeling systematics. However, the results from these two background subtraction methods are in good agreement.

One of the most important factors in this measurement is the modeling of low hadronic energy events. The MC used in the background method includes a detailed detector model together with low hadronic cross section models for the background processes. In addition, the MC modeling includes Fermi motion [6] as well as Pauli suppression [7].

Using the MC based background subtraction method, we obtain $N_{IMD} = 1238 \pm 116(\mathrm{stat}) \pm 300(\mathrm{syst})$ which results in an energy normalized IMD cross section:

$$\sigma_{\mathrm{IMD}}/E_\nu = (16.5 \pm 1.5(\mathrm{stat}) \pm 4.0(\mathrm{syst})) \times 10^{-42}\mathrm{cm}^2/\mathrm{GeV}. \quad (6)$$

Figure 1 shows the comparison between data (solid circles) after background subtraction and the Standard Model MC predictions of IMD signal (histograms). The data is well described by the MC.

Using the direct background subtraction method using the data in antineutrino running mode, we obtain $N_{\mathrm{signal}} = 1066 \pm 188(\mathrm{stat}) \pm 107(\mathrm{syst})$ which results in a cross section value of

$$\sigma_{\mathrm{IMD}}/E_\nu = (14.2 \pm 2.5(\mathrm{stat}) \pm 1.4(\mathrm{syst})) \times 10^{-42}\mathrm{cm}^2/\mathrm{GeV}. \quad (7)$$

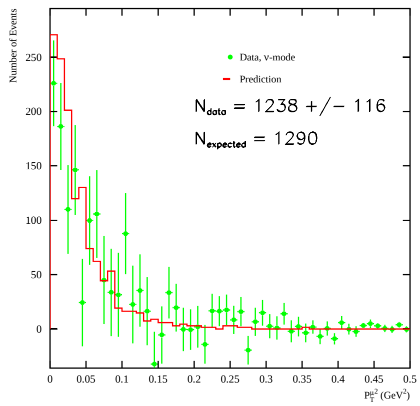

Figure 1. Comparisons between data (solid circle) and MC (histogram) for IMD events after MC based background subtraction.

As can be seen, this method provides a more precise cross section measurement and is in good agreement with the Standard Model prediction: $\sigma_{IMD}/E_\nu = 17.2 \times 10^{-42}\mathrm{cm}^2/\mathrm{GeV}$. This result is also in good agreement with other precise measurements of IMD cross sections [8]. The most important significance of this measurement, however, is that we now have developed a method to precisely estimate the background for Lepton Number Violation measurements.

4 Conclusions

NuTeV has measured $\sin^2\theta_W = 0.2253 \pm 0.0019(\mathrm{stat}) \pm 0.0010(\mathrm{syst})$ which is equivalent to $M_W^{(\mathrm{on-shell})} = 80.26 \pm 0.11\mathrm{GeV/c}^2$. This measurement is the first of its kind using the Paschos-Wolfenstein relationship and provides a measurement of the W boson mass in comparable precision to that from direct measurements.

NuTeV also presents the IMD cross section using a direct subtraction method: $\sigma_{\mathrm{IMD}}/E_\nu = (14.2 \pm 2.5(\mathrm{stat}) \pm 1.4(\mathrm{syst})) \times 10^{-42}\mathrm{cm}^2/\mathrm{GeV}$. This result is consistent with other measurements and Standard Model prediction. In addition, it provides a tool to handle backgrounds for Lepton Number Violating (LNV) processes. The analysis for the LNV process is in progress, and we expect to present the results in the near future.

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