Electroweak Physics at NuTeV

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Abstract. The NuTeV experiment at Fermilab presents a determination of the electroweak mixing angle. High purity, large statistics samples of $\nu_\mu N$ and $\overline{\nu}_\mu N$ events allow the use of the Paschos-Wolfenstein relation, a technique which considerably reduces systematic errors associated with charm production and other sources. Within the Standard Model, this measurement of $\sin^2\theta_W$ indirectly determines the W boson mass to a precision comparable to direct measurements from high energy e^+e^- and $p\bar{p}$ colliders. NuTeV measures $\sin^2\theta_{\mathrm{W}}^{(\mathrm{on-shell})} = 0.2253 \pm 0.0019(\mathrm{stat.}) \pm 0.0010(\mathrm{syst.})$, which implies $M_W = 80.26 \pm 0.11$ GeV. Outside the Standard Model, this result can be used to explore the possibility of new physics; in particular, we present limits on both neutrino oscillations and the presence of extra neutral vector gauge bosons.

In deep inelastic neutrino-nucleon scattering, the weak mixing angle can be extracted from the ratio of neutral current (NC) to charged current (CC) total cross sections. A method for determining $\sin^2\theta_W$ that is much less dependent on sources of model uncertainty and the the details of charm production (the largest source of uncertainty in the previous neutrino measurement [1]) employs the Paschos-Wolfenstein relation [2]:

$$R^- = \frac{\sigma^\nu_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^\nu_{CC} - \sigma^{\bar{\nu}}_{CC}} = \frac{R^\nu - rR^{\overline{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_W \qquad (1)$$

where $R^{\nu,\bar{\nu}} = \sigma^{\nu,\bar{\nu}}_{NC}/\sigma^{\nu,\bar{\nu}}_{CC}$, and $r = \sigma^{\bar{\nu}}_{CC}/\sigma^\nu_{CC}$. Unfortunately, the substantially reduced uncertainties come at a price: R^- is a more difficult quantity to measure experimentally because neutral current neutrino and antineutrino events have identical observed final states. The two samples can only be separated by knowing the incoming neutrino beam type.

High-purity neutrino and antineutrino beams were provided by the Sign Selected Quadrupole Train (SSQT) at the Fermilab Tevatron during the 1996-1997 fixed target run. Neutrinos are produced from the decay of pions and kaons resulting from interactions of 800 GeV protons in a BeO target. Dipole magnets immediately downstream of the proton target bend pions and kaons of specified charge in the direction of the NuTeV detector, while wrong-sign and neutral mesons are stopped in beam dumps. The resulting beam is almost purely neutrino or antineutrino depending on the selected sign of the parent mesons (opposite particle contamination is $\sim$0.1%). In addition, the beam is almost purely muon neutrinos with a small ($\sim$1%) contamination of electron neutrinos.

Neutrino interactions are then observed in the NuTeV detector [3], which is located approximately 1.5 km downstream of the proton target. The detector consists of an 18m long, 690 ton steel-scintillator target followed by an instrumented iron-toroid spectrometer. The target calorimeter is composed of 168 3m x 3m x 5.1cm steel plates interspersed with liquid scintillation counters and drift chambers. The scintillation counters provide triggering information as well as a determination of the longitudinal event vertex, event length and visible energy deposition. The mean position of hits in the drift chambers help establish the transverse event vertex. The toroidal spectrometer, which determines muon sign and momentum, is not directly used for this analysis. In addition, because the detector was continuously calibrated through exposure to a wide energy range of test beam hadrons, electrons and muons, many systematics related to detector effects were substantially reduced.

WITHIN THE STANDARD MODEL

In order to measure $\sin^2\theta_W$, observed neutrino events must be separated into charged current (CC) and neutral current (NC) categories. Both CC and NC neutrino interactions initiate a cascade of hadrons in the target that is registered in both the scintillation counters and drift chambers. However, muon neutrino CC events are distinguished by the presence of a final state muon, which typically penetrates well beyond the hadronic shower and deposits energy in a large number of consecutive scintillation counters. These differing event topologies enable the statistical separation of CC and NC interactions based solely on event length (*i.e.*, on the presence or absence of a muon in an event). Events with a long length (spanning more than 20 counters) are identified as CC candidates; those with a short length (spanning less than 20 counters) as NC candidates. The experimental quantity measured in both neutrino and antineutrino modes is the ratio:

$$\mathrm{R}_{\mathrm{meas}} = \frac{\#\ \text{SHORT events}}{\#\ \text{LONG events}} = \frac{\#\ \text{NC candidates}}{\#\ \text{CC candidates}} \tag{2}$$

The ratios of short to long events ($\mathrm{R}_{\mathrm{meas}}$) measured in the NuTeV data are 0.4198 $\pm$ 0.0008 in the neutrino beam and 0.4215 $\pm$ 0.0017 in the antineutrino beam. A Standard Model value of $\sin^2\theta_W$ can be directly extracted from these measured ratios by using a detailed Monte Carlo simulation of the experiment. The Monte Carlo must include the integrated neutrino fluxes, the neutrino cross section, and a detailed description of the NuTeV detector. More detailed information on the specific components of the Monte Carlo simulation can be found elsewhere [4].

Using our separate high-purity neutrino and antineutrino data sets, NuTeV measures the following linear combination of R^{ν} and $R^{\overline{\nu}}$:

$$R^{-} = R^{\nu} - xR^{\overline{\nu}} \tag{3}$$

The value for x is selected using the Monte Carlo in order to minimize uncertainties related to charm quark production. The single remaining free parameter in the Monte Carlo, $\sin^2\theta_W$, is then varied until the model calculation of R^{-} agrees with what is measured in the data. The preliminary result from the NuTeV data sample for $M_{\rm top}$=175 GeV and $M_{\rm Higgs}$=150 GeV is:

$$\sin^2\theta_W^{(\rm on-shell)} = 0.2253 \pm 0.0019({\rm stat.}) \pm 0.0010({\rm syst.}) \tag{4}$$

Having chosen the convention $\sin^2\theta_W^{(\rm on-shell)} \equiv 1 - \frac{M_W^2}{M_Z^2}$, and given the well-determined Z mass from LEP, our result implies:

$$M_W = 80.26 \pm 0.10({\rm stat.}) \pm 0.05({\rm syst.}) = 80.26 \pm 0.11{\rm GeV} \tag{5}$$

Our measurement is in good agreement with Standard Model expectations, and is consistent with current measurements from W and Z production as well as from other neutrino experiments (Figures 1, 2). The data tend to collectively favor a light Higgs mass. The central value from recent global fits to all precision data is $M_{\rm Higgs} = 98^{+57}_{-38}$ GeV with an upper bound of $M_{\rm Higgs} \leq 235$ GeV at 95% CL [5].

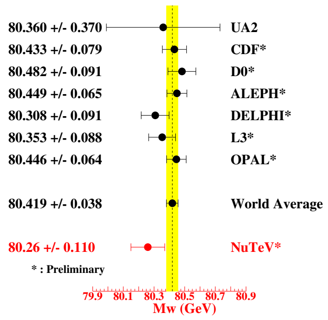

FIGURE 1. Direct W boson mass measurements compared with this result.

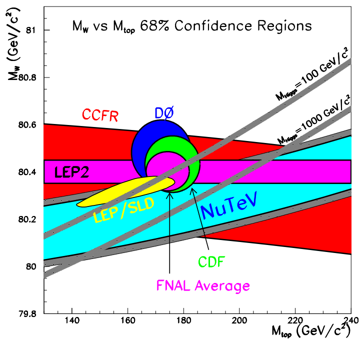

FIGURE 2. Experimental constraints presented on the M_W-$M_{\rm top}$ plane. The two narrow bands indicate the Standard Model predictions for $M_{\rm Higgs}$=100 and 1000 GeV.

BEYOND THE STANDARD MODEL

Outside the Standard Model, deviations between electroweak measurements in νN scattering and those from other processes are sensitive to new physics. In these proceedings we discuss two such possibilities: neutrino oscillations and extra neutral vector gauge bosons.

The presence of neutrino oscillations will directly shift our measured ratios, $R_{\rm meas}$, from their Standard Model predictions. Since ν_μ's oscillating to either ν_e's or ν_τ's would be less likely to produce a final state muon, we would expect to observe an excess of short events. Since no such excess is observed, single mode (ν or $\bar{\nu}$) limits can be set for both $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ oscillations. One advantage to this type of search is that the Paschos-Wolfenstein quantity, R^-, is particularly sensitive to CP-violating oscillations because it is formed from a difference in neutrino and antineutrino rates. As a result, NuTeV is presently the only experiment with direct limits on $\bar{\nu}_\mu \to \bar{\nu}_\tau$. More details on this analysis can be found elsewhere [6].

Extra Z bosons (Z') are of interest not only because they are predicted by many Grand Unified Theories and superstring models, but also in light of recent experimental developments. Erler and Langacker have shown in a recent global fit that the precision electroweak data are better described if an extra TeV-scale Z boson is included [7]. Of course, a large portion of this improvement arises from the fact that the 2.5 σ deviation of the new atomic parity violation (APV) measurement [8] from the Standard Model prediction can be explained by including an additional Z boson [9].

In our case, extra Z bosons would manifest themselves as shifts in the neutrino-quark couplings away from their Standard Model values. These shifts can arise from both pure-Z' exchange as well as from Z-Z' mixing contributions. If we consider constraints on extra Z bosons in E_6 models, then these coupling shifts are well-determined [10]. In this case, the lightest extra Z boson is a linear combination of the SO(10) singlet Z_χ and the SU(5) singlet Z_ψ:

$$Z' = Z_\chi \cos\beta + Z_\psi \sin\beta \qquad (6)$$

expressed in terms of a free parameter β. Our data tend to disfavor the inclusion of additional Z bosons, so we set a 95% CL lower limit on the mass of such an extra Z' plotted as a function of β (Figure 3). Limits are displayed for two cases: the Z' has no mixing with the Standard Model Z, and the more realistic case that allows for some level of mixing. For the latter, we input the Z pole data constraint that the level of Z-Z' mixing is small (10^{-3}) [7]. Note that the inclusion of Z-Z' mixing, even at this small level, weakens the limits. At 95% CL and assuming a 10^{-3} level of Z-Z' mixing, we set lower mass limits of 675 and 380 GeV for the Z_χ and Z_η respectively. Direct searches have already excluded masses below $\sim$ 600 GeV [11].

As can be seen from Figure 3, our maximum sensitivity is to the Z_χ, and our exclusion peaks in the most viable region suggested by the APV data. Figure 4 shows a direct comparison of the region NuTeV excludes in Z' mass-β space to the favored central value from the APV data analyses [9].

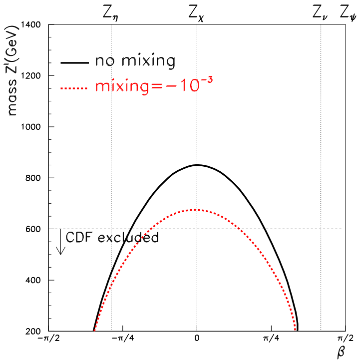

FIGURE 3. NuTeV 95% CL lower limits on the mass of the Z' (in GeV) as a function of the Z_χ, Z_ψ mixing angle β. Limits are shown for both no-mixing and allowed-mixing cases.

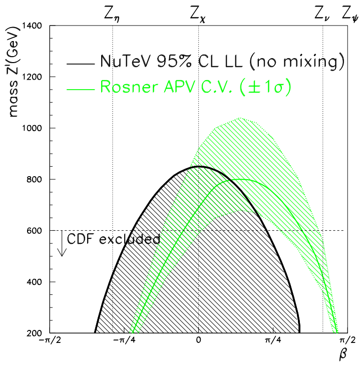

FIGURE 4. Central value from Rosner's APV data analysis [9]. NuTeV excludes the darker shaded region at 95% CL. For purposes of comparison, no Z-Z' mixing has been allowed.

CONCLUSIONS

NuTeV has successfully completed its data taking and has extracted a value of $\sin^2\theta_W$. The precision of this result represents a factor of two improvement over previous measurements in νN scattering, because of reduced uncertainties associated with measuring the Paschos-Wolfenstein ratio, R^-. Interpreted within the framework of the Standard Model, this result is equivalent to a determination of the W mass and is consistent with direct measurements of M_W. Outside the Standard Model, this measurement can be used to set limits on neutrino oscillations as well as extra neutral vector gauge bosons.

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