We present the preliminary result of $\sin^2 \theta_W$ from $\nu-N$ deep inelastic scattering experiment, NuTeV, at Fermilab. This measurement of $\sin^2 \theta_W$ comes from measuring the Paschos-Wolfenstein parameter $R^- = (\sigma_{\nu CC} - \sigma_{\nu NC})/(\sigma_{\bar{\nu} CC} - \sigma_{\bar{\nu} NC})$, using separate beams of $\nu$ and $\bar{\nu}$, utilizing the SSQT. The resulting value of $\sin^2 \theta_W^{(\text{on-shell})}$ is $0.2253 \pm 0.0019\text{(stat)} \pm 0.0010\text{(syst)}$. This value is equivalent to the mass of the W boson, $M_W = 80.26 \pm 0.11\text{GeV/c}^2$. We also summarize the direct measurements of $M_W$ from the Tevatron $\bar{p}p$ collider experiments, DØ and CDF. Combining these two direct measurements yields $M_W = 80.37 \pm 0.08\text{GeV/c}^2$.

1 Introduction

Mass of the W boson ($M_W$) is a fundamental parameter in the electroweak sector of the standard model (SM). The parameters, Fermi constant ($G_F$), the fine structure constant ($\alpha$), mass of the $Z$ boson ($M_Z$), and electroweak radiative correction $\delta r$ are expressed in terms of $M_W$. Among these parameters $G_F$, $\alpha_{\text{EM}}$, and $M_Z$ are measured to very high precision. Thus the measurement of $M_W$ can be used to constrain the mass of the standard model Higgs bosons, $M_H$, together with the measured top quark mass via radiative corrections. In addition, since the radiative corrections take modification with an introduction of new particles, precision measurement of $M_W$ also provides constraint to new physics.

In this paper, we present the preliminary result of $\sin^2 \theta_W$ measurement and the resulting mass of the W boson from $\nu-N$ DIS experiment, NuTeV, at Fermilab. We also summarize the direct measurements of $M_W$ from the Tevatron collider experiments, DØ and CDF.

2 Measurement of $\sin^2 \theta_W$ in $\nu-N$ DIS

In tree level calculations, the electroweak mixing angle, $\sin^2 \theta_W$, appears in neutral current interactions of neutrinos and the calculations have process dependent radiative corrections. The measurement of $\sin^2 \theta_W$ in $\nu-N$ scattering
provides an indirect measure of $M_W$ via electroweak radiative corrections. In addition, since the systematics are uncorrelated to the direct measurements of $M_W$ and the measurement can be done very precisely, the impact of the $\nu - N$ measurement is similar to those from the direct measurements.

Moreover, the comparisons of $M_W$ with those from direct measurements, $Z_0$ line shape, and $\sin^2 \theta_W$ provide sensitivity to new physics. Carrying out a model independent interpretation of $\sin^2 \theta_W$ measured from $\nu - N$ DIS probes light quark couplings which is an extension of the standard model. The measurement is also sensitive to new heavy particles, such as extra $Z$ bosons which affects neutral current couplings. In addition, comparisons of measured ratios of the neutral (NC) to charged current (CC) cross sections provide probes to neutrino oscillations.

### 2.1 Previous Measurement of $\nu - N$ DIS

Since the cross section of CC interactions of neutrinos is proportional to weak isospins ($I_{Weak}^{(3)}$) while that for NC interactions is proportional to ($I_{Weak}^{(3)} - Q_{EM} \sin^2 \theta_W$), the ratio of the CC to NC cross sections is proportional to $\sin^2 \theta_W$ as expressed in the Llewellyn-Smith formula:

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

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 counters with energy deposition above 1/4 of that of a single muon. The NC events have short length due to the absence of the muons in the event, while CC events are long. Thus, the experimentally measured ratio $R_{meas} = N_{short}/N_{long}$, represents the NC to CC cross section ratio, $R_{\nu}$. We vary only the NC couplings in the detailed Monte Carlo (MC), until $R_{meas}$ from the MC matches with $R_{meas}$.

The cross section model in the MC incorporates a leading order (LO) corrected Quark-Parton-Model (QPM), using LO parton distribution functions from the CCFR structure function measurements. The second part of the Monte Carlo simulates detailed detector and beam effects, such as “short” CC events caused by low energy range-out muons or by the muons exiting the detector fiducial volume, “long” NC events due to $\pi/K$ decays and punch through, electron neutrino ($\nu_e$) CC events which appear short in the detector, and other detector effects that affect the event length variable. The detailed MC also includes corrections; 1) electromagnetic and electroweak radiative...
corrections, 2) target isovector effects (∼6% for iron target), 3) higher order QCD effects due to longitudinal structure functions, $R_L$, and 4) effect due to heavy quark productions.

There are two major sources of systematic uncertainties in the CCFR measurements. The first is the theoretical uncertainty due to mass threshold effect in the CC production of charm quark from the scattering off the sea quarks. This effect is modeled by LO slow-rescaling. The parameters in the slow rescaling model are measured by the CCFR experiment, using events with two oppositely charged muons, where $m_c = 1.31 \pm 0.24 GeV/c^2$ and $\kappa = 0.37 \pm 0.05$. The uncertainties in CC cross section calculations due to the above two parameters result in $\delta \sin^2 \theta_W = 0.0027$.

The second source is the lack of precise knowledge on $\nu_e$ flux in the beam. Approximately 80% of the total $\nu_e$ in the CCFR neutrino beam, which is a mixture of $\nu$ and $\bar{\nu}$, come from $K^\pm e^\pm$ decays. The $\nu_e$ from this source is well constrained by observed $K^\pm e^\pm$ spectra. Remaining 16% of $\nu_e$ come from neutral K decays, $K_{Le3}$, whose production cross section is known only to 20%. These two sources constitute 4.1% uncertainty to $N_{\nu_e}$, based on a Monte Carlo study. A direct measurement, based on longitudinal shower development, gives 3.5% uncertainty. Averaging these two uncertainties give 2.9% uncertainty in $N_{\nu_e}$ which results in $\delta \sin^2 \theta_W = 0.0015$. Combining all the errors, the final CCFR result is $\sin^2 \theta_W = 0.2236 \pm 0.0041$ which corresponds to on-shell mass of W boson $M_W = 80.35 \pm 0.21 GeV/c^2$.

### 2.2 Improvements in NuTeV

Minimizing the two large systematic uncertainties requires 1) a technique insensitive to the sea quark distributions and 2) to minimize the number of electron neutrinos in the beam, especially resulting from $K_L$. In order to minimize the uncertainty due to the charm quark production, the NuTeV uses the Paschos-Wolfenstein parameter $R^-$:

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

Since $\sigma^{\nu q} = \sigma^{\bar{\nu} q}$ and $\sigma^{\nu q} = \sigma^{\bar{\nu} q}$, 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 $\nu$ and $\bar{\nu}$. Thus, in order to use this relationship, one needs to be able to distinguish neutrino NC interactions from antineutrino interactions which can only be achieved by having prior knowledge on the beam. To achieve this discrimination, the NuTeV modified the beamline.
to use a Sign-Selected-Quadrupole-Train (SSQT) to select either $\nu$ or $\bar{\nu}$ beam at a given running period.

The uncertainty caused by the $\nu_e$ flux is minimized by adding a 7.8 mrad upward angle to the incident proton beam relative to the horizontal axis which directs to the detector. This upward incident angle together with a dipole stationed immediately behind the production target causes the neutral secondaries (especially $K_L$), oppositely charge secondary mesons, and remnant protons to be directly absorbed into the dumps in the SSQT. The remaining major source of $\nu_e/\bar{\nu}_e$ is $K^{\pm}_{e3}$ decays. The fractional uncertainty on predictions of $\nu_e/\bar{\nu}_e$ from $K^{\pm}_{e3}$ is $\approx 1.5\%$ and is dominated by the uncertainty in $K_{e3}^{\pm}$ branching ratio.

2.3 Result of $\sin^2\theta_W$ from NuTeV

The extraction of $\sin^2\theta_W$ in NuTeV is based on the data sample of 1.3 million neutrino and 0.3 million antineutrino events passing the following set of cuts; hadronic energy measured in the calorimeter above 20GeV to ensure full efficiency of triggers and vertex identification, and the location of the neutrino interaction must be 1) within the central 2/3 of the calorimeter transverse dimension to ensure full acceptance, 2) at least 0.4 m from the upstream end of the calorimeter to minimize non-neutrino backgrounds, and 3) at least 2.4 m from the downstream end to ensure sufficient calorimeter coverage for event length measurement.

The ratios of NC candidates (short length) to CC candidates (long length), $R_{\nu_{\text{meas}}}^{\nu(\bar{\nu})}$, are $0.4198 \pm 0.0008$ and $0.4215 \pm 0.0017$ for neutrino and antineutrino, respectively. As it has been discussed in section 2, $R_{\text{meas}}$ is then related to detailed MC predictions. The detector MC in NuTeV has various improvements to reduce previous experimental systematic uncertainties further, utilizing muons from the upstream neutrino interactions and the information obtained from extensive in-situ and continuous calibration beam. Figure 1 shows the comparisons of the event length variables between data and MC for neutrino (top) and antineutrino modes (bottom), demonstrating good agreements in length distributions, especially in the cut value region.

To extract $\sin^2\theta_W$ in NuTeV, we form a linear combination of $R_{\text{meas}}^{\nu}$ and $R_{\text{meas}}^{\bar{\nu}}$: 

$$R_{\text{meas}}^\nu = R_{\text{meas}}^{\nu} - \alpha R_{\text{meas}}^{\bar{\nu}},$$

where $\alpha$ is determined using the MC such that $R_{\text{meas}}^{-}$ is insensitive to small changes in the CC cross sections due to charm mass threshold effect. For the measurement, the value of $\alpha$ is found to be 0.5136. This technique is essentially
employing the expression in the third term in Eq. 2 instead of the second term which requires separate background estimate and flux normalizations. This technique cancels out large number of systematics by taking the ratios separately in neutrino and antineutrino modes, at the same time largely canceling the uncertainties related to charm quark production from the scattering off the sea. The remaining small uncertainty due to heavy quark production comes from the scattering off the d-valence quark which is Cabbibo suppressed.

Table 1 summarizes various uncertainties in this measurement. The single dominant uncertainty is the data statistical uncertainty whose magnitude is about twice as large as the total systematic uncertainty.

### 2.4 $M_W^{on-shell}$ from $\sin^2 \theta_W$

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

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

$$-0.00142 \times \left( \frac{M_{top}^2 - (175GeV)^2}{(100GeV)^2} \right) + 0.00048 \times \log_e \left( \frac{M_H}{150GeV} \right).$$  

Figure 1: Comparisons of “event length” variable between data and MC for neutrino (top) and antineutrino (bottom) modes. The shaded areas in the inset represent systematic uncertainties and the arrows indicate the cut value for NC and CC distinctions.
Table 1: Summary of uncertainties in NuTeV $\sin^2 \theta_W$ measurements.

| SOURCE OF UNCERTAINTY       | $\delta \sin^2 \theta_W$ |
|-----------------------------|---------------------------|
| Statistics                  |                           |
| Data                        | 0.00188                   |
| Monte Carlo                 | 0.00028                   |
| TOTAL STATISTICS            | 0.00190                   |
| $\nu_e/\bar{\nu}_e$        | 0.00045                   |
| Energy Measurement          | 0.00051                   |
| Event Length                | 0.00036                   |
| TOTAL EXP. SYST.            | 0.00078                   |
| Radiative Corrections       | 0.00051                   |
| Strange/Charmed Sea         | 0.00036                   |
| Charm Mass                  | 0.00009                   |
| $u/d, \pi/d$                | 0.00027                   |
| Longitudinal Structure Func | 0.00004                   |
| Higher Twist                | 0.00011                   |
| TOTAL PHYSICS MODEL         | 0.00070                   |
| TOTAL UNCERTAINTY           | 0.0022                    |

The small residual dependence of this result on $M_{top}$ and $M_H$ comes from the leading terms in the electroweak radiative corrections. Since within the on-shell renormalization scheme, the $\sin^2 \theta_W$ is related to $M_W$ and $M_Z$ together with the standard model prediction of $\rho$, $\sin^2 \theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$, this result is equivalent to:

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

(5)

$$+ 0.073 \times \left( \frac{M_{top} - (175 GeV)^2}{(100 GeV)^2} \right)$$

$$- 0.025 \times \log_{10} \left( \frac{M_H}{150 GeV} \right).$$

Figure 2 shows world measurements of the mass of the W boson. This result is about one standard deviation lower than the world average and is as precise as the measurements from the Tevatron collider experiments. Thus this measurement of $\sin^2 \theta_W$ from the $\nu - N$ scattering contributes significantly to the determination of $M_W$ and thereby constraining the mass of standard model Higgs boson, $M_H$. 
Table 2: Summary of data sample and analyses cuts of the direct $M_W$ measurements.

| Parameters                  | CDF            | DO             |
|-----------------------------|----------------|----------------|
| Decay Channel               | $W \rightarrow \mu + \nu$ | $W \rightarrow e + \nu$ |
| $\int L dt$                | $90 \text{pb}^{-1}$ | $82 \text{pb}^{-1}$ |
| Number of $W$               | 21,000         | 28,000         |
| Number of $Z$               | 1,400          | 2,200          |
| $P_T$ Cut                   | $25 < P_T < 60 \text{GeV}$ | $E_T > 25 \text{GeV}$ |
| $E_T$ Cut                   | $25 < E_T < 60 \text{GeV}$ | $25 < E_T$ |
| Recoil $U_T$ cut            | $U_T < 20$     | $U_T < 15$     |
| Lepton Rapidity cut         | $|\eta_\mu| \leq 1$ | $|\eta_e| \leq 1$ |
| Lepton Quality cuts         | $\mu$ quality  | e-quality      |
|                            | MiP in Calorimeter | Isolation     |
|                            | Cosmic removal   | Shower shape   |
|                            | Track Match      | Track match    |
| $M_{jT}$ Cut                | $50 < M_{jT} < 110 \text{GeV}$ | $50 < M_{jT} < 110 \text{GeV}$ |

Figure 2: Various measurements of $M_W$. 
3 Direct Measurements of $M_W$

Since the effective center of mass energy of Tevatron $\bar{p}p$ collider is higher than the mass of the W boson, $M_W$, real W’s are produced in the collider experiments at $\sqrt{s} = 1.8$ TeV. The DØ and CDF experiments at Fermilab use leptonic decay modes of the W bosons, $W \rightarrow e + \nu$ and $W \rightarrow \mu + \nu$ for DØ and CDF, respectively. The results presented in this paper are based on Tevatron collider run Ib data combined with the Run Ia from both experiments.

The technique used in the direct measurements of $M_W$ in collider experiment relies on both the transverse momentum ($E^l_T$) spectra of charged leptons resulting from the leptonic decays of the W’s or the transverse mass ($M^W_T$) distributions computed using $E^l_T$ and missing momentum ($\not{E}_T$) which infers the neutrino momentum: $M^W_T = \sqrt{2E^l_T E^\nu_T (1 - \cos\phi_{l\nu})}$. Table 2 lists the data sample and the cuts used for the analyses.

The measured $E^l_T$ and $M^W_T$ distributions of the W candidates are then compared to the detailed MC simulations which incorporates detector effects and theoretical models. Since $E^l_T$ and $M^W_T$ are sensitive to the detector energy scale and resolutions, and the underlying events affects the recoil system, both collaborations use $Z \rightarrow ll$ events to measure these systematic effects. The theoretical model incorporated in the detailed MC simulation includes various available next-to-leading order (NLO) parton distribution functions. The momentum distributions of the W’s affect the $E^l_T$ and $M^W_T$ and is modeled by a theoretical predictions with higher-twist effects to account for non-perturbative effects.

Figure 3 shows $M^W_T$ distributions from the DØ and CDF experiments using the electron and muon decay channels, respectively. The lines in the plots are the best MC fit of $M_W$ to the data $M^W_T$ distributions. The same type of MC fits to $E^l_T$ distribution are also performed. Combining the $M_W$ from both the fits in each experiment result in:

$$M_W = 80.38 \pm 0.11 \text{GeV}/c^2 \quad (\text{DØ}) \quad (6)$$
$$M_W = 80.43 \pm 0.12(\text{syst}) \text{GeV}/c^2 \quad (\text{CDF}). \quad (7)$$

Taking the weighted average of these two measurements together with UA2 results in:

$$M_W = 80.37 \pm 0.08 \text{GeV}/c^2. \quad (8)$$

Table 3 summarizes various uncertainties in these measurements from Run Ib data only.
Figure 3: Transverse mass distributions of $W \rightarrow e\nu(\mu\nu)$ events from DØ and CDF.

Table 3: Summary of uncertainties in direct $M_W$ measurements from the DØ and CDF experiments.

| Source                      | $\delta M_W^{CDF}$ (MeV) | $\delta M_W^{DØ}$ (MeV) |
|-----------------------------|--------------------------|--------------------------|
| Statistical                 | 100                      | 70                       |
| Momentum & Energy scale     | 40                       | 65                       |
| Calorimeter linearity       | -                        | 20                       |
| Lepton $P_T$ resolution     | 25                       | 20                       |
| Recoil Modeling             | 90                       | 40                       |
| Input $P_T^W$ and PDF’s     | 50                       | 25                       |
| Radiative decays            | 20                       | 20                       |
| Higher Order Corrections    | 20                       | -                        |
| Backgrounds                 | 25                       | 10                       |
| Lepton Angle Calibration    | -                        | 30                       |
| Momentum Fitting            | 10                       | -                        |
| Other errors                | 20                       | 20                       |
| Total Systematic Uncertainty| 115                      | 70                       |
| Total Uncertainty           | 155                      | 120                      |
4 Constraining Standard Model Higgs Mass

Using the measurements of $M_W$ and the relationship of $M_W$ with $M_{top}$ and $M_H$ via electroweak radiative corrections, one can constrain the standard model higgs mass. Figure 4 shows the 68% confidence level contours from various measurements. Since the NuTeV does not measure $M_{top}$, the result from the NuTeV appears as a band in this plot. Combining all hadron collider direct measurements with NuTeV preliminary result yields the $M_W$ of:

$$M_W = 80.345 \pm 0.055 \text{GeV}/c^2. \quad (9)$$

This mean value of the $M_W$ and the current best measurement of $M_{top}$ would constrain the standard model Higg mass to less than $\sim 500\text{GeV}$.

5 Conclusions

The NuTeV has finished taking its data in September 1997, accumulating $3 \times 10^{18}$ protons on target. The NuTeV presented a preliminary result of $\sin^2 \theta_W$ measurement which is equivalent to the mass of the W boson; $M_W = 80.26 \pm 0.11 \text{GeV}/c^2$. This result is as precise as the direct measurements from
the Tevatron collider experiments. Further improvement in this analysis from the NuTeV experiment is modest because the result is already dominated by data statistical uncertainty. Model independent interpretation of light quark couplings will come soon and the results from other analyses are also expected in the near future.

The two collider experiments are continuing their analyses of Run I data, to further improve the measurements of $M_W$. The CDF experiment expects the total uncertainty reduce to $\sim 90$ MeV, by combining electron decay channel from Run Ib together with the muon decay data. The DØ experiment expects the uncertainty of $\sim 100$ MeV, by including the forward ($|\eta^e| > 1$) electron data.

The direct measurements of $M_W$ are expected to improve dramatically in Tevatron Run II with higher luminosity and upgraded detectors. The expected uncertainty in $M_W$ measurement is on the order of 40-50MeV with the expected $\int \mathcal{L} dt = 2 fb^{-1}$ for each detector. This improvement is expected not only due to improved statistics but also due to various improvements in experimental and theoretical systematic uncertainties, such as better measured detector resolution, recoil $P_T$ due to increased $Z \rightarrow ll$ statistics, better measured $\Gamma_W$, better determined parton distribution functions, improved radiative decays, etc.

Benefiting from all these improvement, the Tevatron measurements of $M_W$ together with the much more precisely measured $M_{top}$ would further constrain the standard model Higgs mass, $M_H$. Combining these indirect constraints on $M_H$ with direct searches would enable the experiments either to find the Higgs bosons or to further constrain $M_H$ to narrow down the regions to be searched in future machines, such as LHC.

References

1. C.H. Llewellyn Smith, Nucl. Phys. B228, 205 (1983)
2. L.W. Whitlow, SLAC-Report-357, 109 (1990).
3. C. Arroyo, B.J. King et. al., Phys. Rev. Lett. 72, 3452 (1994).
4. K.S. McFarland et al., CCFR, Eur. Phys. Jour. C1, 509 (1998)
5. S.A. Rabinowitz et. al., Phys. Rev. Lett. 70, 143 (1993).
6. A. Romosan et. al., Phys. Rev. Lett. 78, 2912 (1997).
7. E.A. Paschos and L. Wolfenstein, Phys. Rev. D7, 91 (1973)
8. D. Yu. Bardin, V.A. Dokuchaeva, JINR-E2-86-260 (1986)
9. K.S. McFarland, NuTeV collaboration, proceedings of the XXXIIIrd Rencontres de Moriond (1998)
10. G.A. Ladinsky and C.P. Yuan, Phys. Rev. D50, 4239 (1994)
11. J. Ellison, proceedings of the XXXIIIrd Rencontres de Moriond (1998)
12. J. Alitti et al., UA2 collaboration, Phys. Lett. B276, 354 (1992)
13. See URL “http://www-cdf.fnal.gov/physics/ewk/ewk.html”