FERMILAB-CONF-93-420
NEVIS R#1489

A PRECISION MEASUREMENT OF $\sin^2\theta_W$ IN NEUTRINO NUCLEON SCATTERING

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Presented by Bruce J. King at the
XXVIIIth Rencontre de Moriond: Electroweak Interactions and Unified Theories,
13–20 March 1993

ABSTRACT

We report a precise measurement of the weak mixing angle from the ratio of the neutral current to charged current inclusive cross-sections in deep-inelastic neutrino-nucleon scattering. Using the on-shell definition, $\sin^2\theta_W \equiv 1 - \frac{M_W{}^2}{M_Z{}^2}$, we obtain $\sin^2\theta_W = 0.2222 \pm 0.0026(\text{stat.}) \pm 0.0035(\text{exp.syst.}) \pm 0.0037(\text{model})$, assuming $M_{top} = 150$ GeV and $M_{Higgs} = 100$ GeV. The data were gathered at the CCFR neutrino detector in the Fermilab quadrupole-triplet wide-band neutrino beam, with neutrino energies up to 600 GeV.

1. Introduction

According to the Standard Model of elementary particle interactions, the ratio, $R_\nu = \sigma_{NC}/\sigma_{CC}$, of the total neutral current (NC) to charged-current (CC) cross-sections in deep-inelastic neutrino-nucleon (νN) scattering,

$$\nu_\mu + \text{nucleon} \rightarrow \nu_\mu + \text{hadrons (NC)}, \tag{1}$$

$$\nu_\mu + \text{nucleon} \rightarrow \mu^- + \text{hadrons (CC)} \tag{2}$$

provides a relatively direct experimental determination of the on-shell weak mixing angle

$$\sin^2\theta_W \equiv 1 - \frac{M_W{}^2}{M_Z{}^2}. \tag{3}$$

In contrast to determinations from other processes, radiative corrections for νN scattering introduce only a minor dependence on the unknown mass of the top quark, M_{top}. This fact also enhances its importance when predicting M_{top} in simultaneous fits to all $\sin^2\theta_W$ measurements. Finally, the consistency of this $\sin^2\theta_W$ with other determinations is uniquely sensitive to several proposed extensions to the Standard Model, including some models with non-minimal Higgs sectors, with extra Z's etc..[1]

2. Data Sample

The E770 event sample, approximately 3 million raw event triggers, was collected in 1987-8 at the Fermilab quadrupole-triplet wide-band neutrino beam-line. The event-weighted neutrino flux spectrum is shown in Figure 1. It contained 86.4% ν_μ, 11.3% $\bar{\nu}_\mu$ and 2.3% ν_e or $\bar{\nu}_e$, with a mean neutrino energy of 164 GeV.

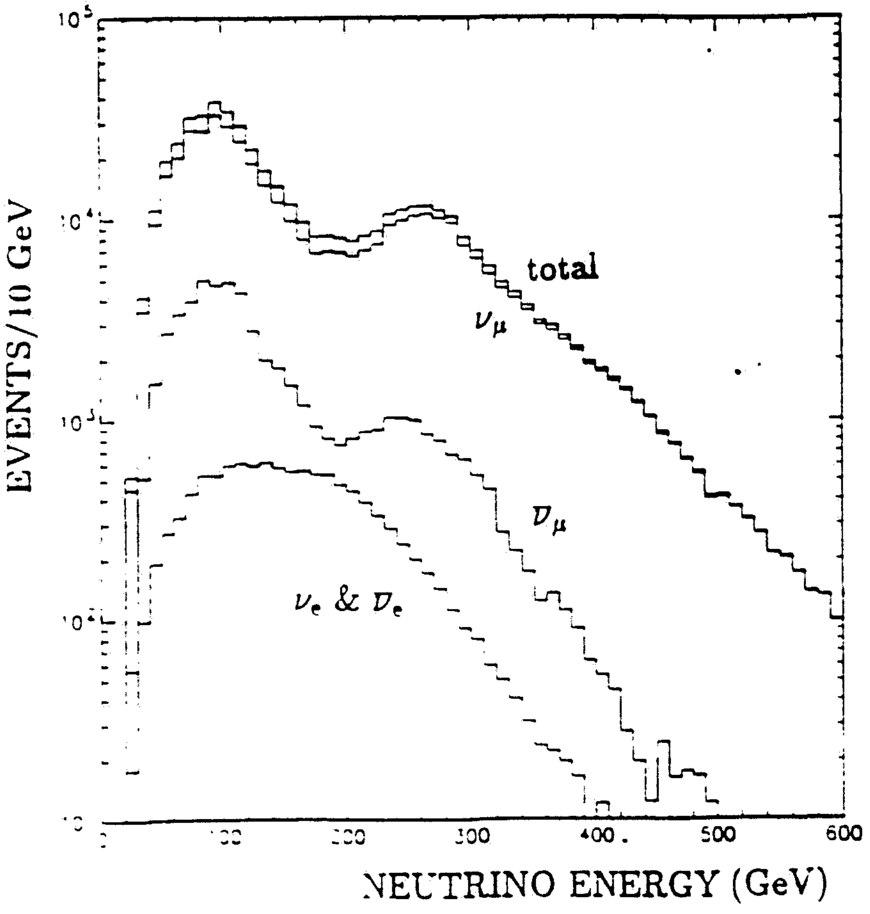

FIGURE 1. The E770 event-weighted neutrino flux spectrum.

The CCFR detector[2,3] consists of a calorimetric target backed by a muon spectrometer. The muon spectrometer was not used directly in the $\sin^2\theta_W$ analysis. The target comprises 168 iron plates, each 3m x 3m x 5.1cm, interspersed with 84 liquid scintillation counters and 42 drift chambers with x and y planes. It is 17.7m long, weights 690 tonnes and has a mean density of 4.2 g/cm^3.

Both CC and NC interactions in the target initiate a cascade of hadrons, which is registered by the drift chambers and scintillation counters. CC, but not NC, interactions also produce a muon, which typically penetrates well beyond the hadron shower. This appears as a track of drift chamber hits, with deposits of characteristic minimum-ionizing energies in the scintillation counters.

We define an event length, L, by counting the number of scintillation counters from the event vertex to the most downstream counter with energy deposition. The radial displacement of the vertex from the detector centre-line is determined from a fit to hits in nearby drift chambers. A calorimetric energy, E_{cal}, is calculated by summing up the equivalent energy depositions in the 20 counters imediately downstream from the vertex. We require the event vertex to be more than 6 counters from the upstream end of the target and 34 counters from the downstream end, with radius less than 76.2 cm. An E_{cal} cut of 30 GeV ensures complete efficiency of the energy deposition trigger.

3. Analysis

The presence of a penetrating muon in CC interactions allows one to define an experimental approximation to R_ν simply by partitioning the final event sample by event length:

$$R_{meas} \equiv \frac{\#\ \text{events with}\ L \leq 30\ \text{counters}}{\#\ \text{events with}\ L > 30\ \text{counters}}, \quad \sim \quad \frac{\#\ NC}{\#\ CC}. \tag{4}$$

The observed ratio for E770, $R_{meas} = 147795/327832 = 0.4508$, was translated into an experimental value for $\sin^2\theta_W$ using a detailed Monte Carlo-based computer simulation ("MC") of the experiment, which models the integrated neutrino fluxes, the relevant physics processes and the response of the CCFR detector.

The ν_μ flux came predominantly from the 2 body decays of pions and kaons. The integrated flux for E770 was estimated directly from the CC ν_μ event sample, normalised to the neutrino total cross-section. Errors in the ν_μ flux tend to cancel in the ratio R_{meas}, but this is not the case for the ν_e contamination. A CC ν_e interaction produces a short electromagnetic shower inside the hadron shower rather than a penetrating muon and is almost always counted in the *numerator* of R_{meas}, along with the true NC interactions. The integrated ν_e flux was modelled using a Monte Carlo simulation of the neutrino beam-line. Fortunately, ~80% of the ν_e's in the final data sample were produced in the Ke3 decay mode of charged kaons, and the modelling of these events could be tuned using the observed ν_μ event spectrum. The next largest contribution to the ν_e flux was from neutral kaon decays (~16%), with smaller contributions from the decays of D mesons, pions, muons, Λ's and Σ^-'s. We estimate a 4.5% uncertainty in the fractional contamination of ν_e's.

Neutrino cross-sections were modelled using a QCD-enhanced quark-parton description of the nucleon. The quark distributions were obtained using nucleon structure functions measured in the same experiment.[4] The strange quark component was determined from an analysis of charm production in dimuon events in the same experiment,[5] which comes largely from CC scattering off strange quarks and anti-quarks. The dimuon analysis also determined the threshold suppresssion of this process due to the massive charm quark. This was parameterized using

the slow-rescaling formalism, with a fitted effective charm mass, $M_c = 1.32 \pm 0.24$ GeV. Estimating the reduction of the CC cross-section due to the charm threshold represents the single biggest physics model uncertainty in the $\sin^2\theta_W$ analysis. The charm sea was estimated to be 15 ± 15% of the strange sea, based on a wrong-sign muon analysis from a previous neutrino experiment using the CCFR detector.[6] A correction for the difference between u and d valence quark distributions in nucleons, consistent with muon scattering data,[7] was applied to account for the 5.67% excess of neutrons over protons in the CCFR target. Radiative corrections to the scattering cross-sections were applied using computer code supplied by Bardin.[8] These assumed $M_{top} = 150$ GeV and $M_{Higgs} = 100$ GeV; the dependence on both of these parameters is very weak.

The development of neutrino-induced events in the detector and resolution smearing effects on the measured L, E_{cal} and vertex positions were modelled, wherever possible, using real events from our neutrino run and extensive hadron, muon and electron test beam data.[2,3,9]

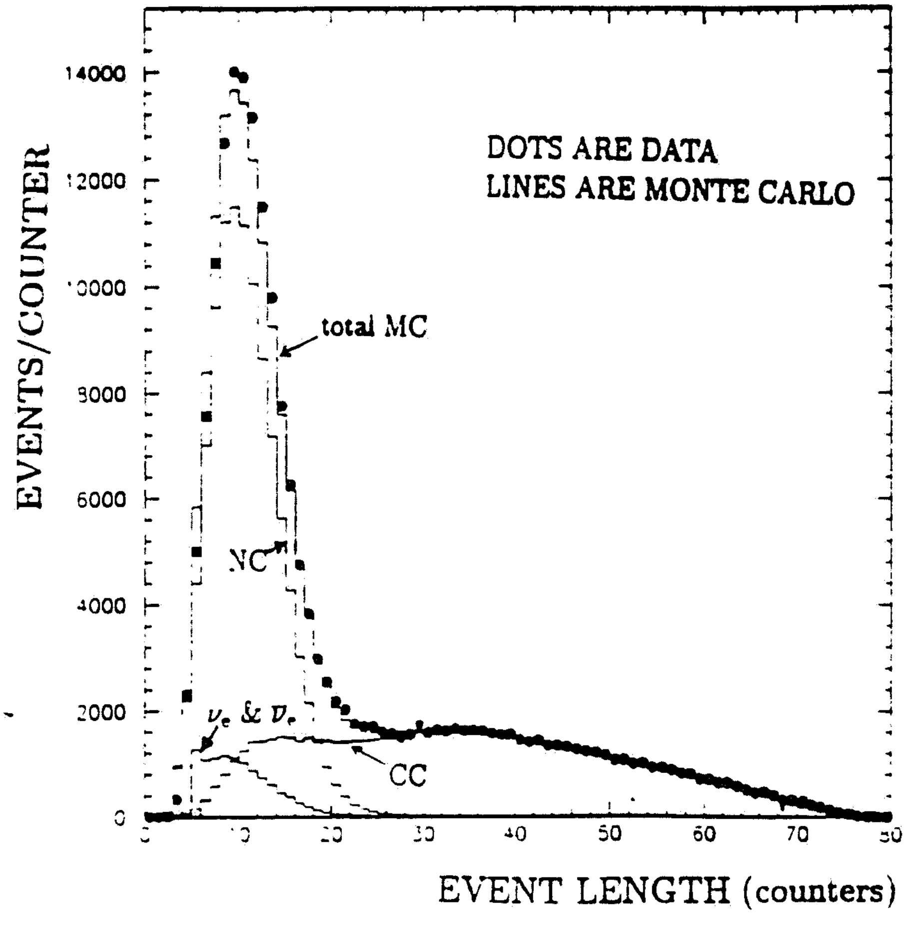

FIGURE 2. **Data and MC event length distributions.**

Figure 2 shows the length distribution of the E770 data and a MC simulated event sample. Events reaching the muon spectrometer, comprising 79% of the CC interactions, have been left out for clarity but are included in the normalization of the MC event sample to the data. The remaining CC events have a muon which either has a low energy and ranges out or has a large opening angle with respect to the incident neutrino and exits the side of the detector. The production energy and angular distributions of these muons is very well constrained by the CCFR structure function measurements, and their propagation through the target has been accurately parameterized using large samples of muons from test beam and neutrino data. The agreement between data and MC for event lengths greater than 30 counters reinforces our confidence in our estimate of the CC component of the event sample in the 'NC' length region of less than or equal to 30 counters. The NC and ν_e event lengths fall well short of the 30 counter separatrix used in the definition of $\mathrm{R_{meas}}$, which demonstrates our insensitivity to the 1/3 counter scale uncertainty in modelling the hadron shower length distribution. The data and MC distributions in $\mathrm{E_{cal}}$ and vertex radius also agree well.

Large samples of simulated events were generated using the MC, and passed through the same analysis procedure as the E770 data to obtain MC estimates, $\mathrm{R^{MC}_{meas}}$, of $\mathrm{R_{meas}}$. The experimental value of $\sin^2\theta_\mathrm{W}$ was then determined as the input value to the MC, $\sin^2\theta^\mathrm{MC}_\mathrm{W}$, for which $\mathrm{R^{MC}_{meas}}$ agreed with $\mathrm{R_{meas}}$. The experimental and theoretical model uncertainties were obtained by varying the relevant model parameters of the MC within their uncertainties and observing the change induced in $\mathrm{R^{MC}_{meas}}$.

4. Results

The relationship between $\mathrm{R^{MC}_{meas}}$ and $\sin^2\theta^\mathrm{MC}_\mathrm{W}$ was found to be given, in a linear approximation, by

$$\sin^2\theta^\mathrm{MC}_\mathrm{W} = 0.2222 - 1.731(\mathrm{R^{MC}_{meas}} - 0.4508). \tag{5}$$

This, combined with our experimental determination, $\mathrm{R_{meas}} = 0.4508 \pm 0.0014$, determines our experimental $\sin^2\theta_\mathrm{W}$ to be

$$\sin^2\theta_\mathrm{W} \;=\; 0.2222 \;\pm\; 0.0026(\mathrm{stat.}) \;\pm\; 0.0035(\mathrm{exp.syst.}) \;\pm\; 0.0037(\mathrm{model}). \tag{6}$$

Table 1 displays the uncertainties contributing to the result. The statistical uncertainty is seen to be equal in size to the largest experimental systematic uncertainty, from the contamination of ν_e's, and the largest physics model uncertainty, from charm production. The correlations between the contributing uncertainties are all small; adding them in quadrature gives a grand total uncertainty of 0.0057.

TABLE 1. Uncertainties in our measurement of $\sin^2\theta_\mathrm{W}$.

data statistics	0.0024
Monte Carlo statistics	0.0009
TOTAL STATISTICS	0.0026
(ν_e± 4.5%) electron neutrino flux	0.0025
muon neutrino flux	0.0015
event length	0.0014
event energy	0.0012
event radius	0.0006
TOTAL EXPERIMENTAL SYSTEMATIC	0.0035
($\mathrm{M_c} = 1.32 \pm 0.24$ GeV) charm production	0.0024
(d(Uv/Dv) = ± 10%) non-isoscalar target	0.0017
(c/s = 0.15± 0.15) charm sea	0.0015
(R_{long}± 10%) long. SF	0.0011
(Bardin vs. de Rujula et al.) rad. corrections	0.0010
($\kappa \pm 0.07$) strange sea	0.0006
(constrained by SF fits) higher twist	0.0005
(vary para. by uncert.) structure functions	0.0003
TOTAL PHYSICS MODEL	0.0037

5. Discussion and Conclusions

The most precise prior measurements of $\sin^2\theta_W$ in νN scattering come from 2 experiments[10,11] in the 1984 CERN 160 GeV narrow band neutrino beam, with published values of $\sin^2\theta_W = 0.228 \pm 0.005 \pm 0.005$ (CDHS) and $\sin^2\theta_W = 0.236 \pm 0.005 \pm 0.005$ (CHARM). Our determination is marginally more precise than either of these, and our central value is slightly lower. However, both of these earlier experiments used low M_{top} masses that have now been ruled out by direct searches at the Fermilab Tevatron collider. Adjusting to the value, $M_{top} = 150$ GeV, used in our analysis lowers the CDHS and CHARM central values to 0.225 and 0.234, respectively, in better agreement with our result.

From the defining equation 3, our $\sin^2\theta_W$ may be trivially combined with the extremely accurate measurement of the Z boson mass, $M_Z = 91.187 \pm 0.007$,[12] to give a determination of the W boson mass. We obtain $M_W = 80.42 \pm 0.29$ GeV. This is consistent with the direct determination, $M_W = 80.22 \pm 0.26$ GeV,[13] and also with the less direct estimate, $M_W = 80.17 \pm 0.14$ GeV, obtained from a M_{top} fit to all other relevant experimental data.[14]

In summary, our value is currently the most accurate determination of $\sin^2\theta_W$ (on-shell definition) in a single experiment and is consistent with previous determinations in νN scattering and other processes.

We acknowledge the gracious help of the Fermi National Accelerator Laboratory staff and the dedicated efforts of many individuals at our home institutions. This research was supported by the U.S. National Science Foundation and the U.S. Department of Energy.

References

1. Reviewed in P. Langacker, M. Luo and A. Mann, Rev. Mod. Phys. **64** (1992) 87
2. W.K. Sakumoto *et al.* (CCFR collab.), Nucl. Inst. Meth. A294 (1990) 179
3. B.J. King *et al.* (CCFR collab.), Nucl. Inst. Meth. A302 (1990) 179
4. P.Z. Quintas *et al.* (CCFR collab.). Submitted for publication in Phys. Rev. Lett.
5. S.A. Rabinowitz *et al.* (CCFR collab.), Phys. Rev. Lett. **70**, 134 (1993)
6. S.R. Mishra *et al.* (CCFR collab.), Z. Phys. **C44**, 187 (1989)
7. P. Amaudruz *et al.* (New Muon Collab.), Nucl. Phys. **B371**, 3 (1992)
8. D. Yu. Bardin and O.M. Fedorenko, Sov. J. Nucl. Phys **30**, 418 (1979); and private communication.
9. F.S Merritt *et al.* (CCFR collab.), Nucl. Inst. Meth. A245 (1986) 27; P.H. Sandler *et al.* (CCFR collab.), Phys. Rev. **D42**, 759 (1990).
10. H. Abramowicz *et al.* (CDHS collab.), Phys. Rev. Lett. **57**, 298 (1986); A. Blondel *et al.* (CDHS collab.), Z. Phys. **C45**, 361 (1990)
11. J.V. Allaby *et al.* (CHARM collab.), Phys. Lett. **B177**, 446 (1986); J.V. Allaby *et al.* (CHARM collab.), Z. Phys. **C36**, 611 (1987)
12. Quoted from Luigi Rolandi, CERN-PPE/92-175, 15 October, 1992
13. A weighted mean of the M_W measurements of the CDF and UA2 collaborations. Quoted from Particle Data Group, Review of Particle Properties, Phys. Rev. **D45**, No. 11 (1992).
14. M_{top} fit performed by Luigi Rolandi, *op. cit.*.