Precise Measurement of the Weak Mixing Angle in Neutrino-Nucleon Scattering

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We report a precise measurement of the weak mixing angle from the ratio of neutral current to charged current inclusive cross sections in deep-inelastic neutrino-nucleon scattering. The data were gathered at the CCFR neutrino detector in the Fermilab quadrupole-triplet neutrino beam, with neutrino energies up to 600 GeV. Using the on-shell definition, $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$, we obtain $\sin^2\theta_W = 0.2218 \pm 0.0025(\text{stat}) \pm 0.0036(\text{expt syst}) \pm 0.0040(\text{model})$.

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The standard model (SM) of elementary particle physics describes the unification of the electromagnetic and weak interactions in terms of a weak mixing angle, $\sin^2\theta_W$. In the on-shell convention [1], the mixing angle is defined in terms of the W and Z boson masses:

$$\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}. \quad (1)$$

This Letter presents a SM extraction of $\sin^2\theta_W$ from the ratio of neutral current (NC) to charged current (CC) total cross sections in deep-inelastic neutrino-nucleon (νN) scattering,

$$\nu_\mu + \text{nucleon} \to \nu_\mu + \text{hadrons (NC)}, \quad (2)$$

$$\nu_\mu + \text{nucleon} \to \mu^- + \text{hadrons (CC)}. \quad (3)$$

The SM predicts that all electroweak processes may be described at lowest order in perturbation theory by just three independent experimental parameters. These may be chosen to be the electromagnetic fine structure constant (α), the Fermi coupling constant (G_F), and the mass of the Z boson (M_Z), all of which have been measured to better than 1 part in 10^4. Electroweak processes cannot yet be predicted to this level of accuracy because higher order perturbative corrections for each process bring in additional dependence on the masses of the undiscovered top quark (M_{top}) and, to a lesser extent, the Higgs boson (M_{Higgs}). Within the SM, the experimental determination of $\sin^2\theta_W$ from νN scattering has very little dependence on M_{top} or M_{Higgs} [2]; in contrast, the SM prediction of $\sin^2\theta_W$ from α, G_F, and M_Z depends strongly on M_{top}. Requiring the $\sin^2\theta_W$ from νN scattering to agree with the prediction using M_Z sets limits on M_{top} which are comparable with the best determinations from Z and W decay experiments at colliders [3]. From a more general perspective, the consistency of the M_{top} determinations from different processes constrains possible physics processes beyond the SM. Neutrino-nucleon scattering is uniquely sensitive to some proposed models with an extended Higgs sector or with extra Z's [4]. Comparing the SM prediction for M_W from νN scattering with the direct measurements at hadron colliders is a further test of the SM which is almost independent of M_{top} and M_{Higgs}.

The E770 event sample of 3.1×10^6 raw event triggers was collected in 1987–1988 using the quadrupole-triplet neutrino beam line at Fermilab. The data sample for the $\sin^2\theta_W$ analysis contained 475 627 events after all cuts, with a mean neutrino energy of 161 GeV and a mean 4-momentum transfer squared, $Q^2 = 36\ \text{GeV}^2/c^2$. This represents approximately 4 times the statistics and almost twice the mean energy and Q^2 of the most precise previous $\sin^2\theta_W$ determinations from νN scattering [5,6].

The CCFR detector [7,8] consists of a neutrino target/calorimeter followed 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 3 m×3 m×5.1 cm, interspersed with 84 liquid scintillation counters (every 10 cm of iron) and 42 drift chambers,

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each with x and y planes. It is 17.7 m long, weighs 695 metric tons, and has a mean density of 4.2 g/cm^3.

Both CC and NC interactions initiate a cascade of hadrons in the target that is registered by the drift chambers and scintillation counters. The muon produced in CC interactions typically penetrates well beyond the end of the hadron shower, appearing as a track of drift chamber hits with deposits of characteristic minimum-ionizing energies in the scintillation counters. We define the event length, L, to be the number of scintillation counters spanned by the event, where the longitudinal event vertex is defined to be the more upstream of the first 2 consecutive counters with more than 4 times the mean energy deposit of minimum ionizing muons ("mip's") [7], and the event end is the counter above the next downstream gap of 3 counters with energies below 0.25 mip's. The mean position of the hits in the drift chambers immediately downstream from the vertex determines the transverse vertex coordinates. A calorimetric energy, $E_{\rm cal}$, is calculated by summing up energy deposits in the 20 counters immediately downstream from the vertex. We require the event vertex to be more than 5 counters from the upstream end of the target and 34 counters from the downstream end and less than 76.2 cm from the detector center line. Requiring $E_{\rm cal} > 30$ GeV ensures complete efficiency of the energy deposition trigger.

The presence of a penetrating muon in CC interactions permits an approximate partition of CC and NC events by event length:

$$R_{\rm meas} \equiv \frac{\text{No. events with } L \leq 30 \text{ counters}}{\text{No. events with } L > 30 \text{ counters}} \approx \frac{\text{No. NC}}{\text{No. CC}}, \tag{4}$$

where $L > 30$ counters implies a penetration greater than about 3.1 m of iron. This experimental quantity was translated into a SM value for $\sin^2\theta_W$ using a detailed Monte Carlo–based computer simulation (MC) of the experiment which modeled the integrated neutrino fluxes, the relevant physics processes, and the response of the CCFR detector. Predicted values for $R_{\rm meas}$ were obtained by generating samples of simulated events and passing them through the same analysis procedure as the E770 data. The experimental value of $\sin^2\theta_W$ was defined to be the input value to the MC which returned the same $R_{\rm meas}$ as the E770 data. The relationship between $R_{\rm meas}$ and $\sin^2\theta_W$ predicted by the MC is found, in a linear approximation, to be $\sin^2\theta_W^{\rm MC} = 0.2218 - 1.73\,(R_{\rm meas}^{\rm MC} - 0.4508)$. Our experimental determination, $R_{\rm meas} = 147\,795/327\,832 = 0.4508$, corresponds to

$$\sin^2\theta_W = 0.2218 \pm 0.0025(\text{stat}) \pm 0.0036(\text{expt syst}) \pm 0.0040(\text{theor}). \tag{5}$$

The experimental and theoretical uncertainties were obtained from the MC by varying the model parameters within errors, and are itemized in Table I.

While the analysis presented here is performed completely within the context of the standard model, our value of $\sin^2\theta_W$ can be used with the MC model to calculate a corrected neutral to charged current event ratio corresponding to the incident $\nu/\overline{\nu}$ flux [9], $R = (\mathrm{NC}^\nu + \mathrm{NC}^{\overline{\nu}})/(\mathrm{CC}^\nu + \mathrm{CC}^{\overline{\nu}}) = 0.3117 \pm 0.0014(\text{stat}) \pm 0.0018(\text{expt syst}) \pm 0.0014(\text{theor})$. This value corresponds to a hadron energy cut of 30 GeV on both CC and NC events. The event ratio is fully corrected for experimental effects such as acceptance, smearing, and the ν_e background but no theoretical corrections are applied other than an isoscalar correction. For the quantity R, the theoretical uncertainty is almost entirely due to the longitudinal structure function, $R_{\rm long}$. In terms of $R^{\nu(\overline{\nu})} = \sigma_{\rm NC}^{\nu(\overline{\nu})}/\sigma_{\rm CC}^{\nu(\overline{\nu})}$, $R \approx 0.895R^\nu + 0.105R^{\overline{\nu}}$. The variation of R with $\sin^2\theta_W$ is very similar to that of $R_{\rm meas}$ and is given by $dR/d\sin^2\theta_W = -0.565$.

The integrated ν_μ and $\overline{\nu}_\mu$ fluxes for E770 were determined directly from low hadron energy CC event samples, normalized to the neutrino total cross sections [10]. The final event sample consisted of 86.4% ν_μ, 11.3% $\overline{\nu}_\mu$, and 2.3% ν_e or $\overline{\nu}_e$ interactions. Errors in the ν_μ flux tend to cancel in the ratio $R_{\rm meas}$, but the ν_e flux modeling is more critical because essentially all ν_e events are short enough to appear in the numerator of $R_{\rm meas}$. The

TABLE I. Uncertainties in the measurement of $\sin^2\theta_W$.

Data statistics	0.0024
Monte Carlo statistics	0.0006
Total statistics	0.0025
Muon neutrino flux	0.0005
Electron neutrino flux ($\nu_e \pm 4.2\%$)	0.0023
Transverse vertex	0.0009
Cosmic ray subtraction ($\pm 25\%$)	0.0003
Energy measurement	
NC/CC shower difference	0.0007
Muon energy loss in shower region	0.0005
Hadron energy resolution ($\pm 10\%$)	0.0005
Absolute energy scale ($\pm 1\%$)	0.0018
Event length	
Hadron shower length	0.0010
Vertex determination (± 2.5 cm)	0.0010
Counter efficiency and noise	0.0009
Dimuon production	0.0003
Total expt. syst.	0.0036
Charm prod. ($M_c = 1.31 \pm 0.24$ GeV/c^2)	0.0030
Long. SF ($R_{\rm long} \mp 15\%$)	0.0019
Charm sea (C/S = 0.10 $\pm$0.15)	0.0015
Rad. corrections	0.0007
Higher twist	0.0005
Nonisoscalar target	0.0004
Strange sea ($\kappa = 0.37 \mp 0.05$)	0.0003
Structure functions	0.0003
Total physics model	0.0040

integrated ν_e flux was modeled using a Monte Carlo simulation of the neutrino beam line, with the spectra of secondaries from the proton target parametrized from experimental production cross sections [11]. Approximately 80% of the ν_e's in the final data sample were produced from the $Ke3$ decay mode of charged kaons, whose modeling is directly related to 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.

The modeling of neutrino-induced events in the detector and resolution smearing effects on the measured L, $E_{\rm cal}$, and vertex positions were modeled primarily using neutrino and test beam data events [7,8,12]. Systematic uncertainties associated with the hadronic energy measurement $E_{\rm cal}$ include possible small NC/CC shower differences, uncertainties in the muon energy deposit within the hadron shower, and uncertainties in the resolution function, e/π response, and absolute energy scales obtained from hadron/electron test beam measurements [7,8]. The length uncertainties include those associated with the shower length parametrizations from test beam measurements [12], the longitudinal vertex determination, which has been checked against the vertex of dimuon events, counter inefficiencies and noise, and effects from dimuon production. Small differences in the transverse vertex for NC and CC events due to the muon drift chamber hits were determined from the analysis of CC events with these hits removed.

The NC and CC differential cross sections were modeled using a QCD-enhanced quark-parton description of the nucleon. The quark distributions were obtained by using a modified Buras-Gaemers parametrization [13] of CC nucleon structure functions measured in the same CCFR experiment [14]. The strange quark component, parametrized by the momentum fraction relative to the nonstrange sea, $\kappa = 2s/(\overline{u}+\overline{d})$, was determined from an analysis of CCFR dimuon events [15] which arise from the muonic decays of charm quarks produced in CC scattering off down and strange quarks and antiquarks. The threshold suppression for this process, due to the mass of the charm quark, was modeled using a leading order slow-rescaling formalism, with a fitted effective charm quark mass of $M_c = 1.31 \pm 0.24$ GeV/c^2 [15]. The level of the charm sea was assumed to be 10% of the strange sea, consistent with a wrong-sign muon analysis from a previous CCFR neutrino experiment using the same detector [16]. Our parametrization of the $R_{\rm long}$ is based on QCD predictions and data from charged lepton scattering experiments [17]. A correction for the difference between u and d valence quark distributions in nucleons, obtained from muon scattering data [18], was applied to account for the 5.67% excess of neutrons over protons in the target. Radiative corrections to the scattering cross sections were applied using a computer code supplied by Bardin [19], assuming values of $M_{\rm top} = 150$ GeV/c^2 and $M_{\rm Higgs} = 100$ GeV/c^2.

Figure 1 shows the length distribution of the E770 final data sample 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 in the neutrino target or has a large opening angle with respect to the incident neutrino and exits through the side of the target. The production energy and angular distributions of these muons are very well constrained by the CCFR structure function measurements, and their propagation through the target has been precisely parametrized using large samples of muons from test beam and neutrino data. The events with length less than or equal to the 30 counter partition of Eq. (4) are predominantly true ν_μ (or $\overline{\nu}_\mu$) NC events, with 22.9% and 7.3% backgrounds from short ν_μ and $\overline{\nu}_\mu$ CC events and ν_e events, respectively. Since the NC and ν_e event lengths fall well short of the 30 counter partition, the sensitivity to the modeling of the hadron shower length is minimal. The good agreement between data and MC for event lengths greater than 25 counters reinforces confidence in the estimate of the CC component of the event sample in the NC length region of 30 counters or less. In addition, the data and MC distributions in $E_{\rm cal}$ and vertex radial position also agree well.

The most precise previous determinations of $\sin^2\theta_W$

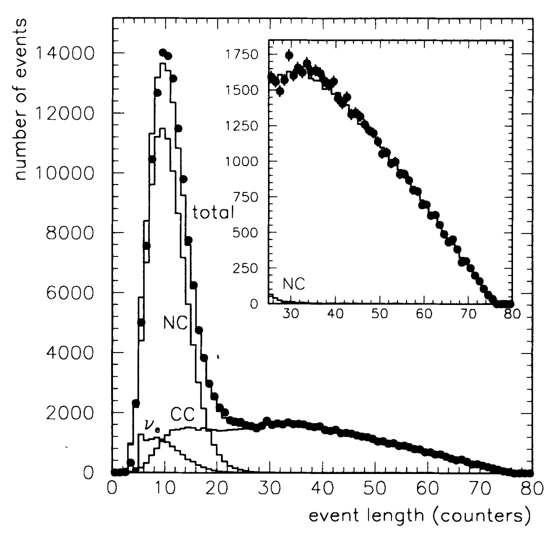

FIG. 1. Data and Monte Carlo (MC) event length distributions. The data are represented by dots and the MC prediction by the solid line. Also shown are the MC contributions from NC ν_μ events ("NC"), CC ν_μ events ("CC"), and combined NC and CC interactions from ν_e or $\overline{\nu}_e$ ("ν_e"). The inset shows the data, total MC, and the NC contribution to the MC for the region $L \geq 25$ counters.

in νN are from the CDHS [5] and CHARM [6] Collaborations. After adjusting to our theoretical assumptions for the charm quark mass, $M_c = 1.31 \pm 0.24$ GeV/c^2 [15], and top quark mass, $M_{\rm top} = 150$ GeV/c^2, these experiments yield measurements of $\sin^2\theta_W = 0.2225 \pm 0.0066$ (CDHS) and $\sin^2\theta_W = 0.2319 \pm 0.0065$ (CHARM), in agreement with our result, $\sin^2\theta_W = 0.2218 \pm 0.0059$.

Combining our value of $\sin^2\theta_W$ with the precise measurement of the Z boson mass, $M_Z = 91.187 \pm 0.007$ GeV/c^2 [20], gives $M_W = 80.44 \pm 0.31$ GeV/c^2, and corresponds in the SM to $M_{\rm top} = 190^{+39+12}_{-48-14}$ GeV/c^2 [21], where the central value and first set of uncertainties assume $M_{\rm Higgs} = 300$ GeV/c^2 and the second set of uncertainties come from varying $M_{\rm Higgs}$ between 60 and 1000 GeV/c^2. Our results are consistent with the values, $M_W = 80.25 \pm 0.10$ GeV/c^2 and $M_{\rm top} = 166^{+17+19}_{-19-22}$ GeV/c^2, from a SM fit to a large number of experimental results from Z decays at the CERN electron collider LEP [3], and our M_W value also agrees with the world average measured value from hadron colliders, $M_W = 80.14 \pm 0.27$ GeV/c^2 [22].

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

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