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A PRECISION MEASUREMENT OF THE WEAK MIXING ANGLE

Presented by Arie Bodek, U. of Rochester, Rochester, NY 14627 (CCFR COLLABORATION)

A. Bodek, H.S. Budd, P. de Barbaro, W.K. Sakumoto, U. Rochester; C.G. Arroyo, B.J. King, K.T. Bachmann, A.O. Bazarko, T. Bolton, C. Foudas, W.C. Lefmann, W.C. Leung, S.R. Mishra, E. Oltman, P.Z. Quintas, S.A. Rabinowitz, F.J. Sciulli, W.G. Seligman, M.H. Shaevitz, Columbia U.; F.S. Merritt, M.J. Oreglia, B.A. Schumm, U. Chicago; R.H. Bernstein, F. Borcherding, H.E. Fisk, M.J. Lamm, W. Marsh, K.W.B. Merritt, H.M. Schellman, D.D. Yovanovitch Fermilab; T. Kinnel, P.H. Sandler, W.H. Smith U. Wisconsin

ABSTRACT

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. Using the on-shell definition, $\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$, we obtain $\sin^2\theta_W = 0.2232 \pm 0.0026(\text{stat.}) \pm 0.0035(\text{exp.syst.}) \pm 0.0037(\text{model})$, assuming $M_{top} = 150$ GeV and $M_{Higgs} = 100$ GeV. The data were gathered at the CCFR neutrino detector in the Fermilab quadrupole-triplet neutrino beam, with neutrino energies up to 600 GeV. The results are insensitive to M_{top} for $M_{top} > 100$ GeV.

The standard model (SM) of elementary particle physics describes the unification of the electromagnetic and weak interactions in terms of the weak mixing angle:

$$\sin^2\theta_W \stackrel{\text{def}}{=} 1 - \frac{M_W^2}{M_Z^2}, \qquad (1)$$

where M_W and M_Z are the masses of the W and Z boson propagators. (This is the 'on-shell' definition of $\sin^2\theta_W$.) This paper describes a determination of $\sin^2\theta_W$ from the ratio, $R_\nu = \sigma_{NC}/\sigma_{CC}$, of neutral current (NC) to charged-current (CC) total cross-sections in deep-inelastic neutrino-nucleon (νN) scattering,

The SM predicts a parametric dependence of the NC coupling on the value of $\sin^2\theta_W$. For the on-shell definition of $\sin^2\theta_W$ this dependence has little uncertainty due to the unknown mass of the top quark (M_{top}), although this is not the case for determinations from other electroweak processes. (Conversely, converting the νN measurements to other common definitions of the weak mixing angle *does* bring in a sizable dependence on M_{top}.) The differing M_{top} dependences of different electroweak processes can be exploited by performing multi-experiment SM fits for the value of M_{top}. The unusual M_{top} independence of νN scattering measurements gives them heavy weighting in these fits.

The E770 event sample of approximately 3 million raw event triggers was collected in 1987-8 at the Fermilab quadrupole-triplet neutrino beam-line.

The CCFR detector consists of a neutrino target backed by a muon spectrometer. The muon spectrometer was not used directly in the $\sin^2\theta_W$ analysis (although it was crucial to the related CCFR analyses mentioned below). The target comprises 168 iron plates, each 3m x 3m x 5.1cm, interspersed with 84 liquid scintillation counters (every $\approx$ 10 cm of iron) and 42 drift chambers, each with x and y planes. It is 17.7m long, weighs 748 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, which is registered by the drift chambers and scintillation counters. The muon produced in CC interactions typically penetrates well beyond the hadron shower, appearing 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 event end. The presence of a penetrating muon in CC interactions allows one to define an experimental approximation to $R_\nu = \sigma_{NC}/\sigma_{CC}$ by partitioning the final event sample by event length:

$$R_{meas} \stackrel{\text{def}}{=} \frac{\#\ \text{events with } L \leq 30 \text{ counters}}{\#\ \text{events with } L > 30 \text{ counters}} \qquad (2)$$

Where 30 counters corresponds to a penetration greater than 3.1 m of iron. 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. The MC models the integrated neutrino fluxes, the relevant physics processes and the response of the CCFR detector.

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 neu-

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trino target 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,

MC predictions for R_{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_{meas} as the E770 data. The experimental and theoretical model uncertainties were obtained from simulated event samples in which one of the model parameters of the MC was varied within its uncertainty with all other parameters fixed at their central values.

The relationship between the MC input value of $\sin^2\theta_W$ and the output value of R_{meas} is given, in a linear approximation, by

$$\sin^2\theta_W^{MC} = 0.2232 - 1.73\,(R_{meas}^{MC} - 0.4508). \qquad (3)$$

Our experimental determination, $R_{meas} = 0.4508 \pm 0.0014$(exp.stat.), corresponds to

$$\sin^2\theta_W \;=\; 0.2232 \pm 0.0026(\text{stat.}) \pm 0.0035(\text{syst.}) \quad (4)$$

and an additional model error of $\pm$ 0.0037 (model).

Table 1 displays the uncertainties contributing to the result. The three largest uncertainties come from modeling charm production, statistics and the ν_e contamination. The correlations between the contributing uncertainties are all small and adding them in quadrature gives a total uncertainty of 0.0058.

The most precise prior measurements of $\sin^2\theta_W$ in νN scattering came from two experiments 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 slightly more precise than either of these, and our central value is a little lower. Both of these earlier experiments assumed 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 1, our $\sin^2\theta_W$ may be trivially combined with the accurate measurement of the Z boson mass, $M_Z = 91.187 \pm 0.007$, to give a determination of the W boson mass. We obtain $M_W = 80.37 \pm 0.29$ GeV. This is consistent with the direct determination (CDF/UA1), $M_W = 80.22 \pm 0.26$ GeV , and also with the less direct estimate, $M_W = 80.17 \pm 0.14$ GeV, obtained from a M_{top} fit to LEP and all other relevant experimental data.

TABLE 1. Uncertainties in the measurement of $\sin^2\theta_W$. The sign of the correlation between model parameter values and the value of $\sin^2\theta_W$ is indicated by the "$\pm$" or "$\mp$" symbol — an increase (decrease) in the chosen value of the parameters labeled "$\pm$" ("$\mp$") would increase $\sin^2\theta_W$ as measured.

data statistics	0.0024
Monte Carlo statistics	0.0006
TOTAL STATISTICS	0.0025
($\nu_e \pm 4.2\%$) electron neutrino flux	0.0023
muon neutrino flux	0.0020
event length	0.0017
event energy	0.0010
event radius	0.0009
($\pm$25%) cosmic ray subtraction	0.0003
TOTAL EXPT. SYSTEMATIC	0.0038
(M_c = 1.32 $\pm$ 0.24 GeV) charm prod.	0.0030
(C/S = 0.10 $\pm$ 0.15) charm sea	0.0015
($R_{long} \mp$ 15%) long. SF	0.0013
rad. corrections	0.0007
higher twist	0.0005
(NMC uncert.) non-isoscalar target	0.0004
($\kappa = 0.37 \mp 0.05$) strange sea	0.0003
structure functions	0.0003
TOTAL PHYSICS MODEL	0.0037

FIG. 1. Data and MC event length distributions.