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Precision Measurement of $\sin^2\theta_W$ from Semileptonic Neutrino Scattering

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The ratio R_ν of the neutral- to charged-current cross sections of neutrinos in iron has been measured in an exposure of the CERN-Dortmund-Heidelberg-Saclay neutrino detector to a 160-GeV/c neutrino narrow-band beam at the CERN Super Proton Synchrotron. The result is $R_\nu = 0.3072 \pm 0.0025(\text{stat}) \pm 0.0020(\text{syst})$, for hadronic energy greater than 10 GeV. The electroweak mixing parameter is $\sin^2\theta_W = 0.225 \pm 0.005(\text{expt}) \pm 0.003(\text{theor}) + 0.013(m_c - 1.5\ \text{GeV}/c^2)$, where m_c is the charm-quark mass.

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There is considerable interest in measurement of the electroweak mixing parameter $\sin^2\theta_W$ of the Glashow-Salam-Weinberg theory[1] as precise as possible: First, its value may be predicted by models of grand unification[2]; second, precise measurements of $\sin^2\theta_W$ from different processes would test the validity of electroweak radiative corrections.[3,4] At present this parameter is most precisely determined in semileptonic neutrino-nucleon scattering from the ratio of neutral-current (NC) to charged-current (CC) cross sections,[5-9] and in proton-antiproton collisions from the W-boson mass.[10,11]

In this paper results are reported from an experiment of the first type. Preliminary results from this experiment have been reported earlier.[12] A more complete report on the experimental details will be published elsewhere.[13] In order to achieve a higher precision of $R_\nu = \text{NC}/\text{CC}$ than in previous experiments, the upgraded CERN-Dortmund-Heidelberg-Saclay detector was exposed to an optimized version of the CERN narrow-band beam (NBB), providing a significant increase in statistics and a reduction of the neutrino-flux uncertainties. The beam was operated at 160-GeV/c parent momentum. The subtraction of the so-called wide-band-beam (WBB) background, due to hadrons of unknown sign and momentum decaying upstream of the decay tunnel, caused the largest systematic error in the previous experiment.[6] To overcome this uncertainty, a movable 1.5-m-long iron dump was installed just before the decay tunnel. Data taken with the dump inserted into the beam line provided a direct measurement of the WBB background. A total of 6×10^{18} protons of 450 GeV/c momentum was delivered on target by the CERN Super Proton Synchrotron. Ninety percent of the data were taken with neutrinos, and ten percent with antineutrinos.

The CERN-Dortmund-Heidelberg-Saclay detector consisted of 21 magnetized iron toroids of 1.875-m radius instrumented with scintillators and drift chambers.[14] For the present experiment the first ten modules were replaced by new ones, with 15-cm-wide scintillator strips alternating in the horizontal and vertical directions. This configuration allowed the determination of the transverse position of hadron showers to a precision of ± 5 cm. The detector was triggered on a local energy deposition (shower trigger) or, independently, on a particle penetrating at least three modules (muon trigger). To avoid any bias between NC and CC events, the event samples were defined from calorimetric and topological information only, with no reference to the muon reconstruction. For every event, the event length L, defined as the longitudinal distance between the vertex and the last scintillator hit in the event, and the shower energy E_{sho}, from the pulse height recorded in the first 1.5 m of iron after the vertex, were measured.

An event was retained if it had a shower trigger and if its vertex lay inside a cylinder of 1.3-m radius around the detector axis, excluding a $20\times20\text{-cm}^2$ area around the central hole, and ranging from the middle of module 3 to the middle of module 10. In order to avoid electronic problems at high trigger rates, a time

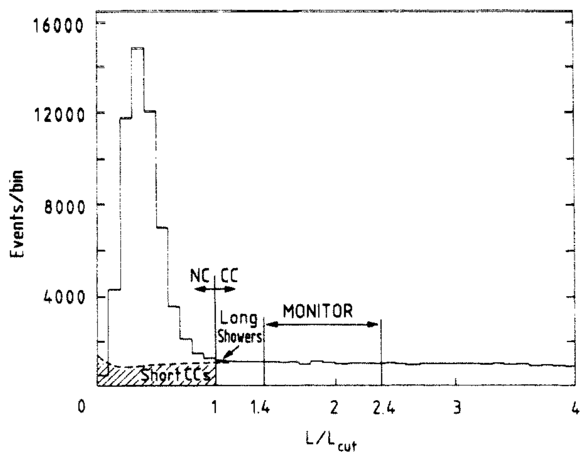

FIG. 1. Distribution of the event length L, in units of the cutoff L_{cut} (see text), for neutrino events with $E_h > 10$ GeV. The background from cosmic rays and WBB has been subtracted. The dashed line shows the Monte Carlo prediction of the muon length in CC events, normalized to the monitor region.

lapse of more than 20 μs with respect to the preceding trigger was required.

The separation of events into NC and CC candidates was done on the basis of the event length as shown in Fig. 1. The cutoff length L_{cut} is defined by $L_{cut} = 75 + 38 \ln[E_{shower}/(1 \text{ GeV})]$, in centimeters of iron, in such a way as to minimize systematic uncertainties from the spillover of NC events into the CC sample.

A cut was applied on the hadron energy, $E_h > 10$ GeV. For NC events, the measured shower energy E_{shower} is identical to E_h. For CC events, E_{shower} also contains the pulse height deposited by the muon in the first 1.5 m of iron. This pulse height, equivalent to typically 3 GeV of hadronic energy, is measured from isolated muon tracks with a precision of $\pm 5\%$. The resulting uncertainty in the E_h cut for CC events induces a systematic error of $\pm 0.3\%$ on R_ν. The efficiency of the shower trigger for $E_{shower} > 10$ GeV was measured to be better than 99.9%, by use of events taken with a muon trigger.

Starting from the raw number of NC and CC candidates, various corrections must be made to obtain the genuine NC and CC event numbers (Table I).

Cosmic-ray events were subtracted by use of data taken between beam spills. The WBB background is subtracted by use of the data taken in "dump in" running conditions.

The migration above L_{cut} of events with no muon or with a primary muon shorter than L_{cut} is mostly due to secondary muons from hadron decay, and was calculated by Monte Carlo simulation. Including also a small contribution from long hadron showers or event lengthening by noise, this "long-shower" correction amounts to $(+0.5 \pm 0.2)\%$ of the NC/CC ratio.

The largest correction is the subtraction of the so-called short CC events from the NC candidates, and their addition to the CC events. These are mostly CC ν_μ events with a muon range shorter than L_{cut}. Because of the magnetic field which bends the muons towards the detector axis and also because of the small radius of the fiducial volume, only 7% of the short CC events have a muon leaving the detector at the side. The number of short CC events is obtained by a Monte Carlo simulation of the muon length distribution, normalized to a monitor region defined as $1.4 \leq L/L_{cut} < 2.4$ (see Fig. 1). This simulation requires the understanding of the y distribution $(y = 1 - E_\mu/E_\nu)$ and of the length measurement. The normalization of the short CC events, $\langle y \rangle = 0.94$, to the monitor region, $\langle y \rangle = 0.85$, is much less sensitive to physics assumptions than would be the normalization to the whole CC sample. The errors induced by the y-distribution uncertainties amount to 0.7% of the correction, primarily from the longitudinal structure function. Because of the normalization to the monitor region, the correction is largely insensitive to errors in the momentum, the divergence, the π/K composition of the parent beam, the muon energy loss, and the hadron energy calibration. It is, however, sensitive to a bias in the measurement of the event length. This was estimated to be less than ± 1.5 cm, corresponding to an error of $\pm 1\%$ on the correction.

The event numbers must finally be corrected for CC events produced by electron neutrinos from K_{e3} decay.

TABLE I. Event numbers and corrections of NC and CC events, for $E_h > 10$ GeV.

	NC	CC	Change of NC/CC and systematic error (%)
Candidates	60 936	137 853	± 0.3
Cosmic rays	-1120	-9	-1.8 ± 0.1
WBB background	-2920	-5187	-1.2 ± 0.1
Long shower	$+159$	-158	$+0.5 \pm 0.2$
Short CC	-9642	$+9526$	-22.5 ± 0.35
K_{e3} correction	-3016	$+2488$	-8.0 ± 0.2
Corrected event numbers	44 397	144 513	± 0.65

These events are included in the NC sample since the final-state electron is hidden in the hadron shower. The absolute rate of CC ν_e events is determined from a Monte Carlo simulation, normalized to the number of fully reconstructed CC ν_μ events from $K_{\mu 2}$ decay. The CC ν_e events are subtracted from the NC sample, and those with $E_h > 10$ GeV are added to the CC sample.

After all these corrections the NC-to-CC cross-section ratio for neutrino interactions in iron, with $E_h > 10$ GeV, is

$$R_\nu = 0.3072 \pm 0.0025(\text{stat}) \pm 0.0020(\text{syst}).$$

Up to small corrections, $\sin^2\theta_W$ can be extracted from the following relation[4]:

$$R_\nu = \tfrac{1}{2} - \sin^2\theta_W + \tfrac{5}{9}\sin^4\theta_W(1+r),$$

where r is the ratio of CC $\bar{\nu}$ to CC ν cross sections integrated over the same neutrino spectrum with the same E_h cutoff. It was measured to be $r = 0.39 \pm 0.01$.

This formula is valid for an isoscalar target, in a world of u, $\bar{u}$, d, $\bar{d}$ quarks and zero quark-mixing angles, and must be corrected for the nonisoscalarity of the target, the presence of s and c quarks in the nucleon, and the charm-quark excitation. These corrections were determined by use of a quark-parton model of the nucleon, including QCD fits to the measured structure functions,[15] charm production according to the slow rescaling model,[16] and quark mixing according to the unitarity-constrained Kobayashi-Maskawa matrix.[17,18] Higher-twist effects are claimed to be small for $E_h > 10$ GeV,[4,19] and were not included. The radiative corrections were calculated according to Wheater and Llewellyn Smith,[20] and $\sin^2\theta_W$ was expressed in the on-shell renormalization scheme.[21]

The parameters of the model and their effects on $\sin^2\theta_W$ are listed in Table II. The largest uncertainty is in the choice of the charm-quark mass m_c which affects the threshold suppression of charm production in CC events. Hence the result on $\sin^2\theta_W$ is given as a function of m_c with $m_c = 1.5$ GeV/c^2 as the central value:

$$\sin^2\theta_W = 0.225 \pm 0.005(\text{expt}) \pm 0.003(\text{theor}) + 0.013(m_c - 1.5\ \text{GeV}/c^2).$$

The experimental error results from the statistical and systematic errors on R_ν and r added in quadrature. The theoretical error excludes the uncertainties on m_c. With $m_c = (1.5 \pm 0.3)$ GeV/c^2 it increases to ± 0.005.

The value of $\sin^2\theta_W$ obtained in this experiment is compatible with earlier results obtained by this group.[6,9] It is also compatible with recent measurements from other semileptonic neutrino experiments,[5,7,8,22] as well as with recent determinations of $\sin^2\theta_W$ from the W mass.[10,11] The good agreement between the values of $\sin^2\theta_W$ obtained from neutrino scattering and from the W mass holds only if electroweak radiative corrections are applied. Without these corrections the values $\sin^2\theta_W = 0.207 \pm 0.008$ from the W mass and $\sin^2\theta_W = 0.236 \pm 0.007$ from this experiment would differ by more than 2 standard deviations.

With the assumption now of the validity of the radiative corrections, a precise determination of the ρ parameter, $\rho = m_W^2/m_Z^2\cos^2\theta_W$, can be obtained. To a very good approximation, ρ^2 is equal to the ratio of the measured value of R_ν to the one predicted for $\sin^2\theta_W = 0.223 \pm 0.008$ as determined from the weighted average of the W mass measurements. Propagating all errors quadratically, one finds $\rho = 0.998 \pm 0.011$, in good agreement with the minimal-standard-model value $\rho = 1$.

It is a pleasure to thank the staff of the CERN Experimental Facilities and Accelerator Divisions for the timely installation of the new NBB line and of its monitoring devices, and for the excellent operation of the accelerator complex. We are grateful to our many technical collaborators from the participating institutes for the construction and maintenance of the detector, and for their help with the running of the experiment. We are indebted to L. Maiani, R. Peccei, R. Petronzio, and R. G. Stuart for helpful discussions on the theoretical interpretation of the experimental results.

TABLE II. Effect of the parameters of the model on $\sin^2\theta_W$. The change of $\sin^2\theta_W$ is given when one parameter is varied leaving all the others at their nominal value.

Parameter	$\Delta \sin^2\theta_W$
Quark generation mixing $\|U_{ud}\|^2 = \|U_{cs}\|^2 = 0.947 \pm 0.006$ $\|U_{us}\|^2 = \|U_{cd}\|^2 = 0.053 \pm 0.006$	$+0.0031 \pm 0.0003$
Longitudinal structure function $\sigma_L/\sigma_T = R_{\text{QCD}} \pm R_{\text{QCD}}$	$+0.0006 \pm 0.0006$
Nonstrange sea $(\bar{u}+\bar{d})/(u+d) = 0.13 \pm 0.02$	$+0.0022 \pm 0.0003$
Strange sea $\bar{s}/\bar{d} = 0.45 \pm 0.10$ at $E_h = 30$ GeV	$+0.0043 \pm 0.0010$
Charm sea $c/s = 0.15 \pm 0.15$	$+0.0003 \pm 0.0003$
Nonisoscalar target (Fe) $d_v/u_v = 0.39 \pm 0.04$	-0.0090 ± 0.0009
Radiative corrections $m_{\text{top}} = 45$ GeV/c^2 $m_{\text{Higgs}} = 100$ GeV/c^2	-0.011 ± 0.002
Uncertainties for a fixed m_c	± 0.003
Charm-quark mass[a] $m_c = (1.5 \pm 0.3)$ GeV/c^2	$+0.010 \pm 0.004$
Total theoretical uncertainty	± 0.005

[a]Also includes the influence of m_c on the determination of structure functions.

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