**A NEW DETERMINATION OF THE ELECTROWEAK MIXING ANGLE
FROM MUON-NEUTRINO ELECTRON SCATTERING**

The CHARM-II Collaboration

D. Geiregat¹, P. Vilain² and G. Wilquet²

Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

F. Bergsma, U. Binder, H. Burkard, Y. Eisenberg³, W. Flegel, H. Grote, T. Mouthuy,
H. Øveras, J. Panman, R. Santacesaria⁴, K. Winter, G. Zacek and V. Zacek
CERN, Geneva, Switzerland

R. Beyer, V. Blobel, F.W. Büsler, C. Foos, L. Gerland, T. Layda,
F. Niebergall, G. Rädcl, P. Stähelin, A. Tadsen and T. Voss
**II. Institut für Experimentalphysik⁵, Universität Hamburg, Hamburg,
Federal Republic of Germany**

Th. Delbar, D. Favart, G. Grègoire and E. Knoops¹
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

P. Gorbunov, E. Grigoriev, V. Khovansky, A. Maslennikov and A. Rosanov⁶
Institute for Theoretical and Experimental Physics, Moscow, USSR

W. Lippich, A. Nathaniel and A. Staude
Sektion Physik der Universität⁵ München, München, Federal Republic of Germany

M. Caria⁷, B. Eckart, A. Ereditato, E. Gorini, F. Grancagnolo, R. Iasevoli, V. Palladino
and P. Strolin
Università e Istituto Nazionale di Fisica Nucleare (INFN), Napoli, Italy

A. Capone⁸, D. De Pedis, E. Di Capua⁹, U. Dore, A. Frenkel-Rambaldi,
P.F. Loverre¹⁰, G. Piredda and D. Zanella
Università 'La Sapienza' e Istituto Nazionale di Fisica Nucleare (INFN), Rome, Italy

Abstract

We are reporting on a new determination of $\sin^2\theta_W$ from the ratio of $\nu_\mu e$ to $\bar{\nu}_\mu e$ scattering cross sections. A new detector designed for this purpose was exposed to the Wide Band Neutrino Beam of the 450 GeV CERN SPS. An analysis of data taken in 1987 and 1988 is presented based on 762 $\nu_\mu e$ and 1017 $\bar{\nu}_\mu e$ events. From the ratio of $\sigma(\nu_\mu e)$ to $\sigma(\bar{\nu}_\mu e)$ we determined $\sin^2\theta^0 = 0.233 \pm 0.012(\text{stat}) \pm 0.008(\text{syst})$ without radiative corrections. With radiative corrections for $m_t = m_H = 100$ GeV we find $\sin^2\theta_W = 0.232 \pm 0.012(\text{stat}) \pm 0.008(\text{syst})$.

(Submitted to Physics Letters B)

1 Inter-University Institute for Nuclear Science, Belgium

2 National Foundation for Scientific Research, Belgium

3 Visitor from the Weizmann Institute, Israel

4 On leave of absence from INFN, Rome, Italy

5 Funded by the Ministry for Research and Technology (BMFT) of the Fed. Rep. Germany under contract numbers 05-4HH22P and 05-4MU12P

6 Presently at CERN, Geneva, Switzerland

7 Dipartimento di Scienze Fisiche, Università di Cagliari, Italy

8 Facoltà di Scienze, Università della Basilicata, Potenza, Italy

9 Dipartimento di Fisica, Università di Ferrara, Italy

10 Facoltà di Agraria, Università della Basilicata, Potenza, Italy

Introduction

It is of great interest to improve the precision of measuring neutral current phenomena. Further progress in our understanding of the electroweak sector is expected to come from an observation of small deviations from the predictions of the Minimal Standard Model [1]. With neutrino scattering, the most precise determination of $\sin^2\Theta_W$ has so far been derived from measurements of deep inelastic neutrino nucleon scattering [2]. At present neutrino energies, this precision is limited by theoretical uncertainties mainly due to the unknown value of the charm quark mass which is needed to describe the charm production threshold. In neutrino electron scattering, however, there is no theoretical uncertainty. Unlike the measurement of $\sin^2\Theta_W$ from the mass-ratio m_W/m_Z , which defines $\sin^2\Theta_W$ in the on-shell scheme [3], all other determinations are subject to radiative corrections which have been carefully considered [3,5]. A comparison of all these measurements of $\sin^2\Theta_W$ provides a test of the Standard Model beyond the tree level, the most precise one coming from the Z^0 mass measurement at e^+e^- colliders.

We are reporting here on a new determination of the electroweak mixing angle from a measurement of the ratio of the cross sections of elastic $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering. This method has been pioneered by the CHARM Collaboration [4]. The data we are presenting have been obtained using a new detector designed for this purpose. It was exposed to horn-focussed wide band neutrino and antineutrino beams at the 450 GeV CERN - SPS. The cross section ratio depends on the value of $\sin^2\Theta_W$ in the Born approximation, through the relation

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3 \frac{1 - 4\sin^2\Theta_W + (16/3)\sin^4\Theta_W}{1 - 4\sin^2\Theta_W + 16\sin^4\Theta_W}$$

QED radiative corrections cancel to a large extent in the ratio and can be neglected [5]. Electroweak radiative corrections, however, change the effective value of $\sin^2\Theta_W$ by an amount which depends on the unknown mass of the top quark m_t and of the Higgs boson m_H [3, 5]. R is not directly experimentally accessible, since it would require pure ν_μ and $\bar{\nu}_\mu$ beams and a measurement with full kinematical acceptance.

In this experiment we measured the number of neutrino electron scattering events in the ν -beam, $N(\nu e)$, and in the $\bar{\nu}$ -beam, $N(\bar{\nu} e)$, with recoil energies in a range of 3 to 24 GeV. $N(\nu e)$ and $N(\bar{\nu} e)$ contain events induced by the main $(\bar{\nu}_\mu)$ helicity components of the ν and $\bar{\nu}$ beams, and events from interactions of wrong helicity muon-neutrinos, electron-neutrinos and electron-antineutrinos.

To extract $\sin^2\Theta_W$ we define an empirical ratio

$$R_{\text{vis}} = \frac{N(\nu e)}{N(\bar{\nu} e)} F,$$

with

$$F = \frac{\int \Phi_{\bar{\nu}_\mu}(E_\nu) E_\nu dE_\nu}{\int \Phi_{\nu_\mu}(E_\nu) E_\nu dE_\nu},$$

the energy weighted flux ratio of the main component of the beams. R_{vis} is a function of $\sin^2\Theta_W$ similar to R . In the case of pure beams of equal energies and full kinematical acceptance R_{vis} coincides with R . Figure 1 shows R and R_{vis} as a function of the electroweak mixing parameters without radiative corrections which we denote by $\sin^2\Theta^0$.

To calculate the small contribution of the electron - (anti) neutrino component to R_{vis} we have assumed that ρ , the ratio of the strength of the neutral to charged current, is equal to unity.

As the measurement of R_{vis} involves only measurements of ratios and does not require absolute knowledge of the efficiency of the event selection and absolute neutrino fluxes, small systematic uncertainties can be achieved.

The Experimental Set-up

Aiming at final statistics of 2000 $\nu_\mu e$ and 2000 $\bar{\nu}_\mu e$ events we have built a new massive, fine-grain and low-density detector which is described in detail elsewhere [6]. This detector consists of a target calorimeter of 796 tonnes mainly of glass followed by a muon spectrometer. The calorimeter is used to detect neutrino interactions, and to measure the energy and direction of particle showers. The calorimeter has in total 154'600 plastic streamer tubes with digital readout of the wires and with 73'920 cathode pick-up strips grouped in 9240 channels for analog readout, orthogonal to the wires. The wire and cathode strip spacings are 1 cm and 2.1 cm, respectively. The calorimeter is divided into 420 detector modules, each module consisting of a 48 mm thick glass plate corresponding to one-half of a radiation length, followed by a plane of streamer tubes (see figure 2). Every fifth module is instrumented with a plane of 20 scintillation counters used for dE/dx measurements. The active area of the modules is $3.70 \times 3.70 \text{ m}^2$. To ensure full containment of the electron showers in the calorimeter the fiducial volume starts with module five and ends with module 391: laterally the fiducial volume is limited to $3.2 \times 3.2 \text{ m}^2$. The mass of the fiducial volume is 547 tonnes. The shower direction is determined in both projections as the line starting at the vertex which divides the shower energy in half. The total visible energy of a shower is obtained by summing the charge of the cathode strips inside the shower. The resolution of the direction and the energy of electron showers is $\sigma(\Theta_e) = 22 \text{ mrad} / \sqrt{E/\text{GeV}}$ and $\sigma(E)/E = 0.3 / \sqrt{E/\text{GeV}}$, as determined in a test beam. The average energy of electrons selected in the analysis is 11 GeV.

The spectrometer is used to determine the momenta of muons produced in charged-current reactions of $\nu_\mu(\bar{\nu}_\mu)$ in the target. The momentum resolution is 14% for 20 GeV/c muons.

This detector was exposed to specially designed horn focussed wide band neutrino and antineutrino beams. In one accelerator cycle (14.4s), two 6 ms long pulses of 450 GeV protons were sent onto a 3 mm diameter Beryllium target, one pulse at the end of the acceleration cycle and the second one 2.8s later. With this double pulsing technique the target cools down sufficiently between pulses to stand up to $1.8 \cdot 10^{13}$ protons per accelerator cycle. In order to select a $\nu_\mu(\bar{\nu}_\mu)$ beam, positive (negative) pions and kaons produced in the target were focussed by a magnetic horn and a reflector. The beam composition and the mean energies are summarized in Table 1. The ν_μ and $\bar{\nu}_\mu$ components were determined by an analysis of quasielastic charged-current events. The ν_e and $\bar{\nu}_e$ components were calculated by Monte Carlo methods.

Data Taking

Typically, three hundred neutrino induced processes took place in the detector per accelerator cycle. Trigger signals from the wires of the streamer tubes were used to select electron candidates and quasielastic scattering events and to sample other reactions. The electron trigger selected events with a shower width and length as

Table 1

The abundances (normalized to the main component) of the different neutrino species and the corresponding mean energies for the neutrino and the antineutrino beam.

beam	components	relative abundance	$\langle E_\nu \rangle$ (GeV)
ν	ν_μ	1.0	23.8 ± 0.5
	$\bar{\nu}_\mu$	0.077 ± 0.004	20.6 ± 1.0
	ν_e	0.0087 ± 0.0013	44.0 ± 2.2
	$\bar{\nu}_e$	0.0017 ± 0.0003	33.8 ± 1.7
$\bar{\nu}$	$\bar{\nu}_\mu$	1.0	19.3 ± 0.4
	ν_μ	0.149 ± 0.008	30.1 ± 1.5
	$\bar{\nu}_e$	0.0071 ± 0.0011	36.5 ± 1.8
	ν_e	0.0043 ± 0.0006	37.0 ± 1.9

expected for electromagnetic showers. An upper bound on the event length was used to reject ν_μ charged current interactions. Single tracks and broad hadronic showers were rejected by bounds on the shower width. The trigger efficiency for electron showers was measured in a test beam [6] and found to be larger than 0.97 between 3 and 40 GeV. Quasielastic scattering events were selected by requiring a minimum penetration of a track into the muon spectrometer and by a bound on the shower activity in the calorimeter. Approximately 80 (60) triggers were accepted in a typical cycle for $1.5 \cdot 10^{13}$ protons on target during the $\nu(\bar{\nu})$ beam exposures. Following each accelerator cycle we recorded ten cosmic ray muons to monitor the response of the detector.

The data sample on which we are reporting here was obtained in 1987 and in 1988 for a total of 200 days. The exposure of $9 \cdot 10^{18}$ protons on target was subdivided into neutrino and antineutrino periods alternating every two to four days.

Measurement of Neutrino Electron Scattering

Neutrino electron scattering events have to be selected from a background of neutrino nucleon scattering reactions which are ten thousand times more abundant. The procedure uses the fact that the neutrino electron scattering events have a single forward electron in the final state, inducing an electromagnetic shower in the target. Electromagnetic showers developing in the calorimeter are characterized by their small width and therefore high density of energy deposition in contrast to hadronic showers. The kinematics of the νe elastic interaction implies that the electron direction is limited to a narrow forward cone for neutrino energies $E_\nu \gg m_e$,

$$E_e \Theta_e^2 = 2(1-y)m_e < 2m_e \quad .$$

where E_e , Θ_e and m_e are the energy, angle with respect to the incoming neutrino direction and mass of the electron and y is the ratio of the electron and the neutrino energy. The $E\Theta^2$ distribution of the semileptonic background reactions is much broader.

The selection of neutrino electron scattering events proceeded as follows:

In the first step, events with many contiguous hits and with a small width were selected. Further rejection of the hadronic background was achieved with an analysis of the topology of the event hit pattern with the method of the "minimal spanning tree" [7].

The second step required the precise reconstruction of the shower vertex and direction. Events inside the fiducial volume with one and only one hit in the first streamer tube plane following the vertex were accepted for further analysis. Showers with additional charged particle tracks starting at the vertex and with backscattering, i.e. with hits upstream of and close to the vertex, were rejected.

Finally, only events with a large fraction of their energy deposited in a narrow band along the shower direction were accepted. The selection efficiency was determined in a test beam and found to be 0.76, independent of energy from 3 to 40 GeV.

The remaining background is composed of semileptonic interactions with an electromagnetic shower in the final state, mainly due to coherent and diffractive π^0 production by neutral current (NC) interactions [8] and quasielastic scattering of a component of electron neutrinos and antineutrinos from K_{e3} - decays.

The $E\Theta^2$ distributions of events selected in the neutrino beam (a) and in the antineutrino beam (b) are shown in figure 3. The pronounced peak of $E\Theta^2 < 3$ MeV is attributed to neutrino electron scattering. To evaluate the number of events due to these reactions the expected distributions in $E\Theta^2$ for the background processes have been modelled using Monte Carlo techniques. The distribution for $(\bar{\nu}_e)N \rightarrow e^+N'$ was constructed starting from observed quasielastic $(\bar{\nu}_\mu)N \rightarrow \mu^+N'$ events. We replaced the muon track in these events by an electron shower of the same direction and energy generated by Monte Carlo simulation: the different neutrino energy spectra and the presence of the inverse muon decay process $\nu_\mu e \rightarrow \mu^- \nu_e$ in the ν_μ quasielastic event sample were taken into account. Events due to coherent as well as diffractive neutral-current production of a single π^0 were simulated following the theoretical description of Rein and Seghal [9] and Bel'kov and Kopeliovich [10]. The simulated events were subjected to the same selection chain as the ν_e candidates. The resulting distributions in $E\Theta^2$ and E were then fitted to the observed ones for $5 < E\Theta^2 < 72$ MeV and $3 < E < 35$ GeV to determine the relative contributions of the background reactions, given in Table 2.

The background composition was independently determined for the subsample of events having their vertex in a glass plate followed by a scintillator plane. The energy loss distribution in the early stage of the electromagnetic shower corresponds to one single charged particle in the case of electron showers, whereas π^0 induced showers start with e^+e^- pairs. The relative abundance of these two components was determined from this energy loss distribution in the background region. The results from the two methods are summarized in Table 2.

Table 2

Ratio of contributions from $\nu_e N \rightarrow e N$ and $\nu N \rightarrow \nu \pi^0 N$ ($3 < E < 35$ GeV) to the background determined from the fit of the $E\Theta^2$ -E distributions and from the energy loss (E_F) in the scintillators following the vertex.

Beam	ν_e/π^0 ($E_F < 8$ MeV)	ν_e/π^0 ($E\Theta^2$ -E distr.)
ν beam	0.20 ± 0.03	0.19 ± 0.02
$\bar{\nu}$ beam	0.25 ± 0.03	0.25 ± 0.02

After subtraction of the background we found $N(\nu e) = 762 \pm 43$ (stat) events in the neutrino data sample and $N(\bar{\nu} e) = 1017 \pm 51$ (stat) events in the antineutrino data sample, with $E\Theta^2 < 3$ MeV and $3 < E < 24$ GeV. The observed shape of the $E\Theta^2$ distributions of these events, shown in figure 4, is in good agreement with that expected from the experimental resolution and kinematics.

These events are due to single electrons, as one can conclude from a study of the subsample of events starting in the glass plate in front of a scintillator. The fraction of neutrino electron scattering events depositing less than 8 MeV in the first scintillator after the vertex is consistent with the spectrum of energy deposition observed in an electron beam.

Several systematic uncertainties affect the background subtraction. They include the uncertainties of the $E\Theta^2$ distributions of quasielastic $\nu_e(\bar{\nu}_e)$ scattering, of the $(\bar{\nu})N \rightarrow (\bar{\nu})\pi^0 N$ processes and of a potential small contribution of inclusive NC events with dominantly electromagnetic final state. In the present analysis the uncertainty from the background subtraction, $\Delta \sin^2\Theta_W = \pm 0.007$, gives the largest contribution to the systematic error of this experiment. Extending the energy range to energies above 24 GeV does not improve the statistical error significantly but leads to larger systematic uncertainties.

Flux Normalisation

The value of the empirical ratio R_{vis} is obtained from the ratio of ν_e and $\bar{\nu}_e$ events in combination with the energy-weighted $\bar{\nu}_\mu$ to ν_μ flux ratio F . We determined the flux ratio in four independent ways: from the number of events recorded in the neutrino and antineutrino beams induced by *inclusive* NC and CC processes on nucleons and the known cross section ratio [11], from the number of NC produced π^0 events recorded in the range $5 < E\Theta^2 < 72$ MeV, from the number of *quasielastic* CC processes recorded in the range $0.05 < Q^2 < 0.15$ GeV² and from the integrated *muon flux* recorded in the shield for neutrino and antineutrino runs. The results are summarized in Table 3.

Table 3

Summary of the energy-weighted $\bar{\nu}_\mu$ and ν_μ flux ratio $F = \int \Phi_{\bar{\nu}_\mu}(E_\nu) E_\nu dE_\nu / \int \Phi_{\nu_\mu}(E_\nu) E_\nu dE_\nu$ determined by four independent methods.

method	$F \pm \text{syst. error}$
inclusive	1.166 ± 0.058
quasi-elastic	1.270 ± 0.063
$(-)\bar{\nu}_N \rightarrow (-)\bar{\nu}\pi^0 N$	1.220 ± 0.061
muon flux	1.207 ± 0.049
mean value	1.215 ± 0.028

The *inclusive* processes have a cross section which rises linearly with energy, and the ratio of the energy-weighted fluxes is given by

$$F = N(\bar{\nu}) \sigma_0(\nu) / N(\nu) \sigma_0(\bar{\nu}),$$

where $N(\bar{\nu})$ [$N(\nu)$] are the number of events and $\sigma_0(\nu)$ [$\sigma_0(\bar{\nu})$] the cross section slopes for deep inelastic scattering [11] of neutrinos and antineutrinos. Corrections for wrong-helicity muon-neutrinos and for ν_e and $\bar{\nu}_e$ contributions (Table 1) have been applied. The systematic error is dominated by the uncertainty in the correction for the energy threshold, and in the cross section ratio which is not so well measured below $E_\nu = 30$ GeV.

The cross sections of neutrino and antineutrino *quasielastic* scattering at low Q^2 and high energy are nearly equal; a correction for the small difference was applied. Events with a muon of the correct charge traversing at least two magnet modules and producing only one hit in the detector plane following the vertex were counted. Events with a muon of the opposite charge were counted separately. The corresponding mean neutrino energies were determined from the muon momentum spectra using an unfolding procedure of the resolution and acceptance effects [12]; they are summarized in Table 1. The samples contain events induced by the quasielastic reactions, and by neutrino-nucleon interactions producing $\Delta(1232)$ and higher nucleon resonances. Neutrino and antineutrino induced reactions have different hadronic final states; a Monte Carlo simulation was used to determine the efficiency of the selection criteria of the two sets of data. Events were further selected for small Q^2 ($0.05 < Q^2 < 0.15$ GeV^2), excluding the region $Q^2 < 0.05$ GeV^2 where inverse muon decay events are observed in the neutrino beam. The ratio of the sum of the efficiency weighted cross sections of the three channels mentioned above for the neutrino and antineutrino samples is 0.95 ± 0.05 ; the error of this ratio dominates the systematic uncertainty of the determination of the energy weighted flux ratio.

Neutral-current induced coherent and diffractive π^0 production on nuclei proceeds by axial-vector interaction because of the pseudoscalar nature of pions. The cross sections for neutrinos and antineutrinos are therefore equal. Contributions from the resonance region are effectively excluded by the energy threshold of 3 GeV. We used the number of events recorded in the $E\Theta^2$ range from 5 to 72 MeV as an internal flux monitor. The systematic uncertainty is mainly due to the subtraction of the $(\bar{\nu}_e N \rightarrow e N')$ contribution.

The *flux of muons* produced by the decay of pions and kaons in the beam was measured with a system of solid state detectors inserted into gaps in the shield behind 10 m and 30 m of iron [13] following the decay tunnel. Their relative response was calibrated against a moveable set of counters. The relation between the neutrino-antineutrino flux ratio and the corresponding muon flux ratio is only weakly dependent on the pion and kaon production spectra used in the Monte Carlo simulation resulting in a systematic uncertainty of $\pm 2\%$. The dominating errors arise from instabilities of the beam profile and from uncertainties in the beam composition.

These four methods for flux monitoring are affected in different ways by deadtime effects. Corrections for these dead time effects and for double events due to random overlays were applied.

The four normalization factors agree within their errors, their weighted mean value $F = 1.215 \pm 0.028$ was used in determining R_{vis} .

Since the ratio of the mean energies does not only enter into the flux normalization its uncertainty will be taken into account separately in the determination of $\sin^2\Theta_W$.

Determination of $\sin^2\Theta_W$

Multiplying the ratio of the number of neutrino-electron and antineutrino-electron scattering events with the flux ratio F , we obtained

$$R_{\text{vis}} = 0.910 \pm 0.068 (\text{stat}) \pm 0.045 (\text{syst})$$

which leads to

$$\sin^2\Theta^0 = 0.233 \pm 0.012 (\text{stat}) \pm 0.008 (\text{syst}).$$

Applying electroweak radiative corrections with $m_t = 100 \text{ GeV}$ and $m_H = 100 \text{ GeV}$ [5] gives

$$\sin^2\Theta_W = 0.232 \pm 0.012 (\text{stat}) \pm 0.008 (\text{syst}).$$

The systematic error on $\sin^2\Theta_W$ contains contributions from uncertainties of the flux normalization (± 0.003), of the abundance of wrong-helicity muon neutrinos (± 0.001) and of electron-neutrinos (± 0.002), of the mean energies of the different beam components (± 0.002), from the background subtraction (± 0.007) and from the energy calibration of the detector (± 0.002); they were combined quadratically.

This new result is compared in Table 4 with those obtained in other recent neutrino-electron scattering and deep inelastic neutrino scattering experiments and with those derived from measurements of the W and the Z boson masses. To make this comparison possible, electro-weak radiative corrections have been applied for $m_t = 100 \text{ GeV}$ and $m_H = 100 \text{ GeV}$, following the method of Bardin and Dokuchaeva [5].

Starting with the results derived from neutrino-electron scattering based on the cross section ratio, the CHARM Collaboration [4] and the US-Japan Collaboration (E734 at BNL) [14] obtained a combined result of $\sin^2\Theta_W = 0.202 \pm 0.020$ which was lower than the result from neutrino-nucleon scattering by 0.03 ± 0.02 . The result presented here, although compatible with these older measurements, is in excellent agreement with the average value obtained with neutrino nucleon scattering [2] provided m_t is lower than 257 GeV (90% c.l.). Table 4 also gives the values of $\sin^2\Theta^0$ without electroweak radiative corrections. The agreement among the different methods is clearly improved by taking the radiative corrections into account.

The comparison of $\sin^2\Theta_W$ derived from neutrino-electron scattering and from the new precise measurement of the Z^0 mass shows good agreement with the prediction of the Standard Model. To evaluate the radiative corrections we used the relation [15]

$$\delta_Z = 1 - \left(\frac{A_0}{\sin \Theta^0 \cos \Theta^0 m_Z} \right)^2$$

where $\sin^2\Theta^0$ is the value derived from neutrino electron scattering before radiative corrections are applied and $A_0 = 37.281$ GeV. For m_Z we used the average of the measurements at the Fermi National Accelerator Laboratory [16], at CERN [17] and at the Stanford Linear Collider [18]. $m_Z = 91.09 \pm 0.16$ GeV and obtained

$$\delta_Z(\text{exp}) = 0.063 \pm 0.039.$$

δ_Z incorporates the radiative corrections relating muon decay, neutrino electron scattering and m_Z .

$$\delta_Z = \Delta r - \frac{\Delta \sin^2\Theta}{\sin^2\Theta^0} (1 - \Delta r) (1 - \tan^2\Theta^0 - \Delta \sin^2\Theta / \cos^2\Theta^0),$$

where Δr and $\Delta \sin^2\Theta$ are given in footnote [19].

We obtain for $m_t = m_H = 100$ GeV

$$\delta_Z(\text{theor}) = 0.0592 \pm 0.0013.$$

δ_Z depends less strongly on m_t than Δr [20].

In conclusion, the new result of $\sin^2\Theta_W$ derived from neutrino electron scattering presented here provides a new and important test of the Standard Model when compared to deep inelastic neutrino scattering and the recent precise measurements of m_Z .

Further data are being collected and the analysis is being refined.

Acknowledgements

We gratefully acknowledge the skill and dedication of our many technical collaborators who have contributed to the realization and the operation of the detector and of its associated systems. The experiment has been made possible by grants from the Inter-University Institute for Nuclear Science (Belgium), CERN (Geneva, Switzerland), the Bundesministerium für Forschung und Technologie (Fed. Rep. Germany), the Institute of Theoretical and Experimental Physics (Moscow, Soviet Union), and the Istituto Nazionale di Fisica Nucleare (Italy); we gratefully acknowledge their support. We should like to thank J.M. Maugain and his collaborators for their competent assistance ensuring the excellent performance of the neutrino facility. The accumulation of a large data sample in this experiment has been made possible thanks to the skilful crew operating the CERN Super Proton Synchrotron. We are indebted to T. Bauche, D. Braun, K. De Winter, B. Emsens, K. Nieuwenhuis and A. Seiden for contributions at the early phase of the experiment and to D.Yu. Bardin, for discussions on radiative corrections.

Table 4

Summary of recent determinations of $\sin^2\Theta^0$ and of $\sin^2\Theta_W$
after radiative correction for $m_t = 100$ GeV and $m_H = 100$ GeV.

method	group	$\sin^2\Theta_W$	$\sin^2\Theta^0$
$\sigma(\nu_\mu e)/\sigma(\bar{\nu}_\mu e)$	CHARM II (this experiment)	$0.232 \pm 0.012(\text{stat}) \pm 0.008(\text{syst})$	0.233
	CHARM [4]	$0.210 \pm 0.035(\text{stat}) \pm 0.011(\text{syst})$	0.211
	E734 [14]	$0.198 \pm 0.020(\text{stat}) \pm 0.013(\text{syst})$	0.199
$\sigma^{NC}(\nu)/\sigma^{CC}(\nu)$	CHARM and CDHS [2]	$0.230 \pm 0.004(\text{exp}) \pm 0.005(\text{syst})$	0.240
$\langle m_Z \rangle = 91.09 \pm$ 0.16 GeV	CDF [16] UA2 [17] MARK II [18]	0.2304 ± 0.0012	0.2128

References

- [11] W.J. Marciano and A. Sirlin, Physics Rev. D29(1984)945
- [12] J.V. Allaby et al., CHARM Collaboration, Z. Phys. C36(1987)611, give $\sin^2\Theta_W = 0.235 \pm 0.005(\text{exp}) \pm 0.005(\text{theor})$ for $m_t = m_H = 100$ GeV.
H. Abramowicz et al., CDHSW Collaboration, Phys. Rev. Letters 57(1986)298.
The final analysis of the CDHSW Collaboration gives $\sin^2\Theta_W = 0.226 \pm 0.005(\text{exp}) \pm 0.005(\text{theor})$ for $m_t = m_H = 100$ GeV (CERN/EP 89-101).
The combined result for $m_t = m_H = 100$ GeV is $\sin^2\Theta_W = 0.230 \pm 0.004(\text{exp}) \pm 0.005(\text{theor})$.
- [13] S. Sarantakos, A. Sirlin and W.J. Marciano, Nucl. Phys. B217(1983)84.
M.J. Marciano and S. Sirlin, Phys. Rev. D22(1980)2695, D29(1984)945, D31(1985)213 E.
- [14] J. Dorenbosch et al., CHARM Collaboration, Z Phys. C41(1989)567
- [15] D.Y. Bardin and O.M. Dokuchaeva, Nucl. Phys. B246(1984)221, and preprint JINR-E2-86-260(1986)
- [16] K. De Winter et al., CHARM II Collaboration, Nucl. Inst. Methods A278(1989)670
- [17] K. De Winter et al., CHARM II Collaboration, Nucl. Inst. Methods A277(1989)178
- [18] F. Bergsma et al., CHARM Collaboration, Phys. Lett. 157B(1985)469
- [19] D. Rein and L.M. Sehgal, Nucl. Phys. B223(1983)29
- [10] A.A. Bel'kov and B.Z. Kopeliovich, Sov. J. Nucl. Phys. 46(1987)499
- [111] J.V. Allaby et al., CHARM Collaboration, Z. Phys. C38(1988)403 and Particle Data Group, Phys. Lett. 204B(1988)1
- [12] V. Blobel, DESY 84-118(1984)
- [13] E.H.M. Heijne, CERN 83-06(1983)
- [14] K. Abe et al., Phys. Rev. Letters 58(1987)636
- [15] U. Amaldi et al., Phys. Rev. D36(1987)1385.
- [16] F. Abe et al., CDF Collaboration, Phys. Rev. Lett. 63(1989)720.
- [17] UA2 Collaboration, presented by A. Weidberg, XIV Intern. Symposium on Lepton and Photon Interactions, to be published (Stanford, 1989).
- [18] G.S. Abrams et al. MARK II Collaboration, Phys. Rev. Lett. 63(1989)724 and more recent results reported by G. Feldman and the XIV Intern. Symposium on Lepton and Photon Interactions, to be published (Stanford, 1989).
- [19] F. Jegerlehner, Z. Phys. C32(1986)195, gives $\Delta r = 0.0552 \pm 0.0013$ for $m_t = m_H = 100$ GeV; $\Delta \sin^2\Theta = -0.0014$ is the radiative correction of $\sin^2\Theta^0$ for neutrino electron scattering in the conditions of this experiment (R_{vis}) [5].
- [20] The theoretical value for m_t in the range 80 GeV to 180 GeV is $\delta_Z = 0.07264 - 1.348 \cdot 10^{-4} \cdot m_t/\text{GeV}$.

Figure 1 Ratio of $\sigma(\nu_\mu e)$ and $\sigma(\bar{\nu}_\mu e)$ as a function of $\sin^2 \theta^0$ (without radiative corrections). The dashed curve (R) represents the case of full energy acceptance and pure ν_μ and $\bar{\nu}_\mu$ beams. The full curve (R_{vis}) is valid for the electron energy range 3-24 GeV and takes into account the fractions of wrong-helicity muon neutrinos and of ν_e and $\bar{\nu}_e$. The value of R_{vis} measured in this experiment and the corresponding value of $\sin^2 \theta^0$ are shown.

Figure 2 Details of the detector structure. All dimensions in mm.

Figure 3 Distribution of selected events as a function of $E\theta^2$, (a) in the neutrino, (b) in the antineutrino beam. The background reactions $\nu_e N \rightarrow e N'$ and $\bar{\nu} N \rightarrow \bar{\nu} \pi^0 N$ are shown separately.

Figure 4 Distribution of neutrino electron scattering events as a function of $E\theta^2$, (a) in the neutrino (b) in the antineutrino beam, after subtraction of the background. The points represent the expected distributions.