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MEASUREMENT OF THE RATIO OF THE CROSS-SECTIONS OF MUON NEUTRINO AND ANTINEUTRINO SCATTERING ON ELECTRONS

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ABSTRACT

The ratio R of muon neutrino-electron and antineutrino-electron cross-sections has been determined based on a sample of 46 ± 12 neutrino events and 77 ± 19 antineutrino events obtained in the CHARM fine-grain calorimeter using the CERN Super Proton Synchrotron horn-focused wide-band beams. The experimental result is $R = 1.37 ^{+0.65}_{-0.44}$, corresponding to a value of $\sin^2 \theta_W = 0.215 \pm 0.040$. The systematic error of $\sin^2 \theta_W$ is estimated to be ±0.015.

We report on an experimental determination of the ratio of muon neutrino-electron and antineutrino-electron cross-sections. The cross-sections for the two reactions

$$\nu_\mu e \rightarrow \nu_\mu e \tag{1}$$

$$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e \tag{2}$$

have been measured using the same detector; their ratio therefore determines the coupling constants of the leptonic weak neutral current with an experimental uncertainty which is smaller than in a measurement of a single cross-section. In particular, many of the systematic errors tend to cancel out in the ratio.

The result will be compared with the prediction of the standard model of electroweak interactions [1]. In this model the ratio R is a function of the weak mixing angle $\sin^2 \theta_w$

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

The data have been collected using the fine-grain CHARM detector [2] exposed to the horn-focused wide-band neutrino beam of the CERN 400 GeV Super Proton Synchrotron (SPS). The spectrum of the neutrino beam was computed using a simulation program developed at CERN [3]. It was found to agree with the spectrum deduced from the energy distribution of muons produced in elastic and quasi-elastic neutrino interactions [4]. The average neutrino and antineutrino energies are 31 GeV and 24 GeV, respectively. In two exposures of 1.4×10^{18} and 5.7×10^{18} protons on target, 1.3×10^6 neutrino interactions and 1.4×10^6 antineutrino interactions, respectively, were observed in the 80 t fiducial mass of the detector. About 80% of the antineutrino data used in the present determination of the cross-section ratio have already been used for the determination of the absolute antineutrino-electron scattering cross-section [5].

The same selection criteria have now been used to extract both the neutrino and the antineutrino candidate events. This guarantees that the electron shower detection efficiency is the same for neutrino and antineutrino events. The criteria are those developed for the analysis published previously [5].

The candidates have been searched for among events appearing as narrow showers, which is the characteristic of showers initiated by a single electron, photon, or π^0 [6]. The angle θ between the shower axis and the direction of the incoming neutrino beam was required to be smaller than 100 mrad. Only events with a shower energy E deposited in the calorimeter between 7.5 GeV and 30 GeV have been retained in the final sample. The $E^2\theta^2$ distributions of the 267 neutrino and 665 antineutrino selected events having $E^2\theta^2 < 0.54$ GeV^2 are shown in fig. 1. The measured electron energy and angular resolutions [6] imply that 90% of the $\overset{(-)}{\nu}_\mu e$ events have $E^2\theta^2$ less than 0.12 GeV^2, corresponding to the first two bins in figs. 1a and 1b.

The number of genuine $\overset{(-)}{\nu}_\mu e$ events in the region $E^2\theta^2 < 0.12$ GeV^2 (forward region) was obtained by extrapolating the background from the region $0.12 < E^2\theta^2 <$ < 0.54 GeV^2 (reference region). We assumed that the background is due to two sources:

a) elastic and quasi-elastic charged-current events induced by the ν_e and $\bar{\nu}_e$ contamination of the beam;

b) neutral-current events with γ and/or π^0 in the final state produced by coherent scattering of muon neutrinos on nuclei.

The normalization of background (a) and (b) was obtained, as in the previously published analysis [5], by a study of the energy deposition (E_f) in the first scintillator plane following the shower vertex. This analysis is based on the observation that electromagnetic showers initiated by one or more photons almost always deposit in this scintillator plane an energy larger than one minimum ionizing particle (6 MeV), whilst a large fraction of the showers due to single electrons give an energy deposition corresponding to one minimum ionizing particle. This is clearly seen in fig. 2: fig. 2a shows the E_f distribution for 15 GeV electrons as measured in a test run; fig. 2b shows the distribution obtained by selecting neutrino-induced events belonging to a kinematic region where the production of photons and π^0's dominates. The sample shown has been obtained by applying the cuts $E^2\theta^2 > 0.54$ GeV^2 and $7.5 < E < 17.5$ GeV.

The number of events attributed to background (a) is obtained from the number of events with $E_f < 8$ MeV [*1] in the region $0.12 < E^2\theta^2 < 0.54$ GeV^2, and from the known efficiency of this cut for elastic and quasi-elastic $\overset{(-)}{\nu}_e$-induced events [*2]. The remainder was attributed to background (b).

The $E^2\theta^2$ distribution of background (a), known to be energy-independent, has been determined by folding the measured $E^2\theta^2$ distributions of elastic and quasi-elastic charged-current reactions induced by muon neutrinos and antineutrinos [4] with the measured electron energy and angular resolutions [6]. For this process, the ratio (forward rate)/(reference rate) is 0.49. The $E^2\theta^2$ distribution of background (b) was calculated using the predictions for coherent π^0 production by neutrinos on nuclei [7]. The ratio (forward rate)/(reference rate) is 0.39. Since the two ratios are not very different, a possible error in the composition of the total background has little effect on the final result.

The results of this analysis are summarized in table 1, and the shapes of the two backgrounds are shown in figs. 1a and 1b.

The amount of background (a) found in the ν and $\bar{\nu}$ beam exposures agrees with the background expected from the computed ν_e and $\bar{\nu}_e$ contamination of these beams [2]. The number of the neutrino and antineutrino events attributed to background (b) corresponds to a cross-section ratio compatible with 1. This supports the hypothesis that these events are due to coherent scattering of muon neutrinos on nuclei.

So far, no assumption has been made regarding the nature of the forward peak, whether caused by electrons or by photons produced in an unknown exotic process.

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*1) In the previous analysis [5], we chose $E_f < 9$ MeV. This is a good choice in the antineutrino case because the backgrounds (a) and (b) are of the same order of magnitude (see table 1). In the neutrino beam, background (b) (π^0 and/or γ) dominates, and a harder cut in E_f is necessary in order to reduce the contamination of the one minimum ionizing particle peak at 6 MeV due to the tail of events having two particles in the first scintillator plane.

*2) The efficiency of the cut $E_f < 8$ MeV for the showers induced by reaction (a) was deduced by using the events with visible energy between 30 and 50 GeV and $0.12 < E^2\theta^2 < 0.54$ GeV^2. The result is (0.26 ± 0.06) and is equal for neutrino and antineutrino events. This number is in agreement, within the large errors, with the measured efficiency for single electrons (0.32 ± 0.05). Since the true efficiency for quasi-elastic events is expected to be somewhat smaller than that measured in a test beam, because in a fraction of neutrino-induced events the electron is accompanied by other charged particles, the value (0.26 ± 0.06) was used in the analysis.

There is, however, an alternative method of analysing the data, which is selectively sensitive to electrons. It is based on the selection of a clean sample of electron-induced showers by the requirement $E_f < 8$ MeV. The $E^2\theta^2$ distributions for the 32 selected neutrino and 123 antineutrino events with $E^2\theta^2 < 1.08$ GeV^2 are shown in figs. 1c and 1d. Since the background (b) is cut by requiring $E_f < 8$ MeV, by fitting the shape of background (a) to the events having $E^2\theta^2 > 0.12$ GeV^2, (10 ± 4) events are attributed to the signal in the case of neutrino exposure and (25 ± 8) events in the antineutrino case, in good agreement with the two signals derived from the full samples of events and the efficiency of (0.32 ± 0.05) for detecting electrons (see footnote *2).

The first method of analysing the data was carried out for different energy windows, and gave the energy distribution of the signal and of the two backgrounds shown in fig. 3 together with their expected behaviour, based on a simulation of the energy spectra of the beams and the energy dependence of the reactions involved. The energy distribution of backgrounds (a) and (b) is in agreement, within the large errors, with that expected for elastic and quasi-elastic charged-current $\overset{(-)}{\nu}_e$ and neutral-current $\overset{(-)}{\nu}_\mu$ induced events, confirming once more the validity of the assumptions in the procedure for subtracting the backgrounds.

In order to calculate the cross-section ratio R, one has to know the flux of the various types of neutrinos in the two beams. The ratios $\bar{\nu}_\mu/\nu_\mu$ in the neutrino beam and $\nu_\mu/\bar{\nu}_\mu$ in the antineutrino beam were experimentally determined from the observed μ^+/μ^- (μ^-/μ^+) ratios of elastic and quasi-elastic charged-current reactions [4], whilst the $\nu_e(\bar{\nu}_e)$ contaminations were computed using the wide-band beam Monte Carlo simulation program [3]. The energy-weighted ratios of the components of the two beams are:

$$\text{the } \nu \text{ beam:} \quad \nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 1.00 : 0.03 : 0.016 : 0.003 \tag{4}$$

$$\text{the } \bar{\nu} \text{ beam:} \quad \bar{\nu}_\mu : \nu_\mu : \bar{\nu}_e : \nu_e = 1.00 : 0.12 : 0.013 : 0.007 \,. \tag{5}$$

According to (4) and (5) and assuming $\sin^2\theta_W = 0.22$ to correct for the contamination by wrong-kind neutrinos, we attribute (42 ± 11) events of the total (46 ± 12) to reaction (1) and (64 ± 16) of the total (77 ± 19) to reaction (2).

The neutrino fluxes were monitored in two ways:

i) by measuring the number of inclusive neutrino and antineutrino interactions on nucleons induced by each beam in the same fiducial volume of the calorimeter, making use of the known neutrino-nucleon and antineutrino-nucleon total cross-sections [8];

ii) by measuring the number of single μ^- (μ^+) events induced by quasi-elastic ν_μ ($\bar{\nu}_\mu$)-nucleon interactions in the fiducial volume of the calorimeter [3], making use of the equality of the cross-sections for exclusive neutrino- and antineutrino-nucleon interactions on an isoscalar target.

The inclusive cross-section rises linearly with the neutrino energy, whilst the exclusive cross-sections are constant in the energy domain of the neutrino beams used in this experiment. The normalization by the inclusive events takes into account implicitly the different mean energy of the neutrino and antineutrino beam energy spectra, whereas normalizing to the exclusive events requires the mean energies to be computed from the energy distributions of the events. The corrections to be applied to inclusive or exclusive events are therefore different. The inclusive events have different inelasticity distributions for ν_μ- and $\bar{\nu}_\mu$-induced events, and the correction for the finite shower energy cut ($E \geq 2$ GeV) is, therefore, different for the two beams. The quasi-elastic events, which by definition have zero inelasticity, require an equivalent correction to take into account the experimental muon momentum cut ($p \geq 10$ GeV/c) which was used in a previous analysis [4]. The different neutrino components in the beams require a further correction for the total number of inclusive semileptonic events, whereas the sign of the produced muons automatically monitors the main component of the beam. Some of the systematic errors implicit in the normalization procedure were monitored by the time variation of the ratio between the two normalization factors during the three years of running. The observed r.m.s. variation is 4%.

The visible cross-section σ_{vis} is the fraction of the total cross-section which satisfies the requirement imposed on the recoil electron energy in this analysis: $7.5 \leq E \leq 30$ GeV. In the framework of the standard model of electroweak interactions the inelasticity distribution is a function of $\sin^2 \theta_w$, and the relationship between σ_{vis} and σ_{tot} depends on $\sin^2 \theta_w$.

By using the procedure outlined in ref. 4 we obtain the following cross-sections:

$$\frac{\sigma(\nu_\mu e)}{E_\nu} = \left[2.1 \pm 0.55 \text{ (stat)} \pm 0.49 \text{ (syst)}\right] \times 10^{-42} \text{ cm}^2/\text{GeV}$$

$$\frac{\sigma(\bar{\nu}_\mu e)}{E_{\bar{\nu}}} = \left[1.6 \pm 0.35 \text{ (stat)} \pm 0.36 \text{ (syst)}\right] \times 10^{-42} \text{ cm}^2/\text{GeV} . \qquad (6)$$

The second value agrees, within the errors, with the published value which is based on 80% of the total statistics [5]. The systematic errors due to the uncertainties in the knowledge of the background, in the normalization procedure and in the efficiency in selecting electrons, are still large. However, they are strongly correlated and partially cancel in taking the ratio of the two rates.

In fig. 4 the dashed curve represents the expected cross-section ratio according to formula (3) for the case of full energy acceptance. In comparing with the experimental results, one has to take into account the experimental energy cuts (solid curve) representing the ratio

$$R_{vis}(\sin^2 \theta_w) = \frac{\sigma_{vis}(\nu_\mu e)}{\sigma_{vis}(\bar{\nu}_\mu e)} .$$

The integration of σ_{vis} over the energy spectra of the beams takes into account the effect on the electron energy cuts of the energy resolution of the calorimeter. Here again one can appreciate the advantage of the ratio method: the difference between the two curves is very small around $\sin^2 \theta_w = 0.25$, implying that the uncertainties of the spectra and of the energy cuts have little influence on the final result.

The ratio of the normalized number of $\nu_\mu e$ and $\bar{\nu}_\mu e$ events is

$$R_{exp} = \frac{N(\nu_\mu e)}{N(\bar{\nu}_\mu e)} \times F = \frac{42 \pm 11}{64 \pm 16} \times 2.09 = 1.37 \begin{array}{l} + 0.65 \\ - 0.44 \end{array} \text{ (stat)} , \qquad (7)$$

where $N(\nu_\mu e)$ and $N(\bar{\nu}_\mu e)$ are the number of events induced by muon neutrino and antineutrino elastic scattering interactions, and $F = 2.09 \pm 0.15$ is the ratio of $\bar{\nu}_\mu$ and ν_μ energy-weighted fluxes. Its value is the average of the results of the two previously described normalization methods.

The measured quantity R_{exp} agrees with the predicted $R_{vis}(\sin^2\theta_w)$ for

$$\sin^2\theta_w = 0.215 \pm 0.040 \text{ (stat)} ,$$

as shown in fig. 4, without ambiguity with larger values.

The main sources of systematic uncertainty on R are due to the background subtraction (±10%) and to the normalization (±7%).

The error in the background subtraction has been evaluated by varying the shapes and the amounts of background (a) and (b) in a correlated way for the neutrino and antineutrino cases. The error in the normalization factor was estimated from the stability of the procedures used, as discussed above, and from the difference between the results for the two methods. The systematic error on R, obtained by adding these two components quadratically, leads to the final result

$$\sin^2\theta_w = 0.215 \pm 0.040 \text{ (stat)} \pm 0.015 \text{ (syst)} . \qquad (8)$$

Within the framework of the $SU(2)_L \times U(1)$ theory the neutrino and antineutrino cross-sections can be expressed in terms of the electroweak mixing angle ($\sin^2\theta_w$) and a multiplying factor (ρ^2) equal to the ratio of the over-all strengths of neutral-current and charged-current couplings. The parameter ρ can be related to the isospin of the Higgs system [9], and in the standard model it is equal to 1. The simultaneous measurement of R and $\sigma(\overset{(-)}{\nu}_\mu e)$ allow a determination of ρ, with the result

$$\rho = 1.12 \pm 0.12 \text{ (stat)} \pm 0.11 \text{ (syst)} ,$$

in good agreement with the prediction of the standard model.

In summary, the new determination [eq. (8)] of the value of the weak mixing angle, derived from the ratio of the measured cross-sections of two purely leptonic neutral-current processes, is less affected by systematic errors than the one obtained from the value of a single leptonic cross-section alone, and is not subject to theoretical uncertainty due to the value of ρ^2. It agrees within the statistical error with the values previously found in leptonic and semileptonic [10] reactions, thus favouring a universal coupling of leptons and quarks to the weak neutral current.

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Table 1

"Signal" and "Background" in the forward and reference regions

Beam	ν	$\bar{\nu}$
Reference region: $0.12 < E^2\theta^2 < 0.54$ GeV^2		
Background, electron-induced (a)	40 ± 14	194 ± 28
photon-induced (b)	112 ± 19	202 ± 35
Tail of signal	5 ± 1	8 ± 2
Total number of events	157 ± 13	404 ± 20
Forward region $E^2\theta^2 < 0.12$ GeV^2		
Background, electron-induced (a)	20 ± 7	95 ± 14
photon-induced (b)	44 ± 7	79 ± 14
Bulk of signal	46 ± 12	77 ± 19
Total number of events	110 ± 10	251 ± 16

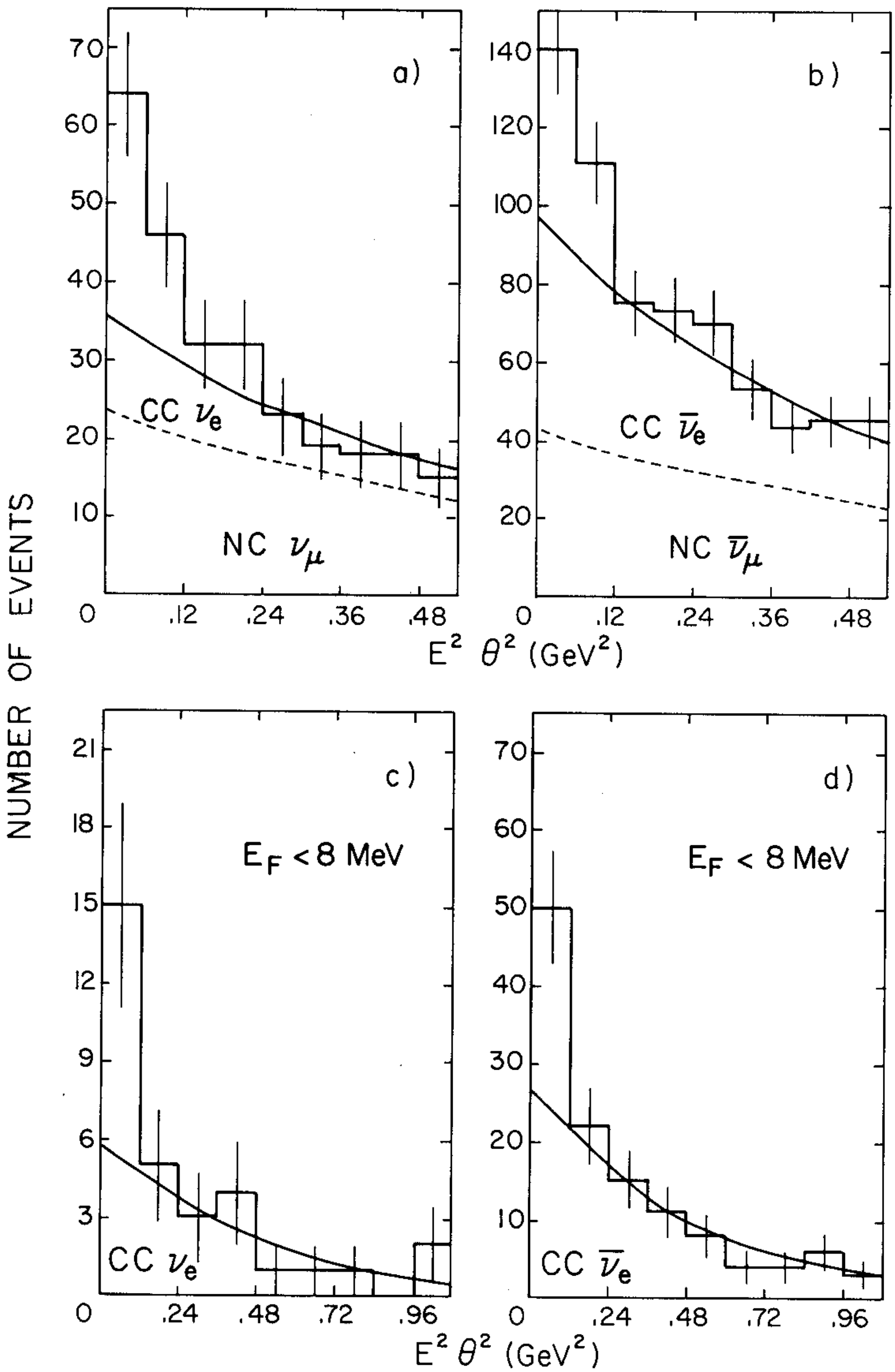
Figure captions

Fig. 1 : Distributions of the candidate events as a function of $E^2\theta^2$ a) for neutrinos, b) for antineutrinos. The backgrounds of CC $\overset{(-)}{\nu}_e$ events and NC $\overset{(-)}{\nu}_\mu$ events, shown in the figures, are discussed in the text. Figures 1c and 1d show neutrino- and antineutrino-induced events satisfying the additional criterion that the energy deposition in the first scintillator plane traversed by the showers is $E_f < 8$ MeV. In this case the background is only due to $\overset{(-)}{\nu}_e$ quasi-elastic scattering.

Fig. 2 : Measured distributions of the energy deposition in the first scintillator plane following the shower vertex: a) Showers induced by 15 GeV electrons traversing, on the average, half a marble slab (0.45 radiation lengths). b) Photon-induced showers produced by neutrino and antineutrino beams in an energy-angle range where photon-induced showers due to coherent processes dominate ($7.5 < E < 17.5$ GeV, $E^2\theta^2 > 0.54$ GeV^2). The contamination due to electron-induced showers is estimated to be 15%.

Fig. 3 : Distribution of the shower energy E deposited in the calorimeter for the events attributed to signal and to background (a) [CC $\overset{(-)}{\nu}_e$], and to background (b) [NC $\overset{(-)}{\nu}_\mu$]. The curves show the expected distributions.

Fig. 4 : Ratio of muon neutrino-electron to antineutrino-electron cross-sections as a function of $\sin^2\theta_W$. The full curve represents the expectation for events in the energy range 7.5 to 30 GeV. The dashed curve represents the expectation in the case of full energy acceptance. The measured value of R and its statistical error are shown together with the corresponding values for $\sin^2\theta_W$.



NUMBER OF EVENTS
a)
CC ν_e
NC ν_μ
b)
CC $\bar{\nu}_e$
NC $\bar{\nu}_\mu$
c)
E_F < 8 MeV
CC ν_e
d)
E_F < 8 MeV
CC $\bar{\nu}_e$
$E^2\ \theta^2$ (GeV^2)
$E^2\ \theta^2$ (GeV^2)

Fig. 1

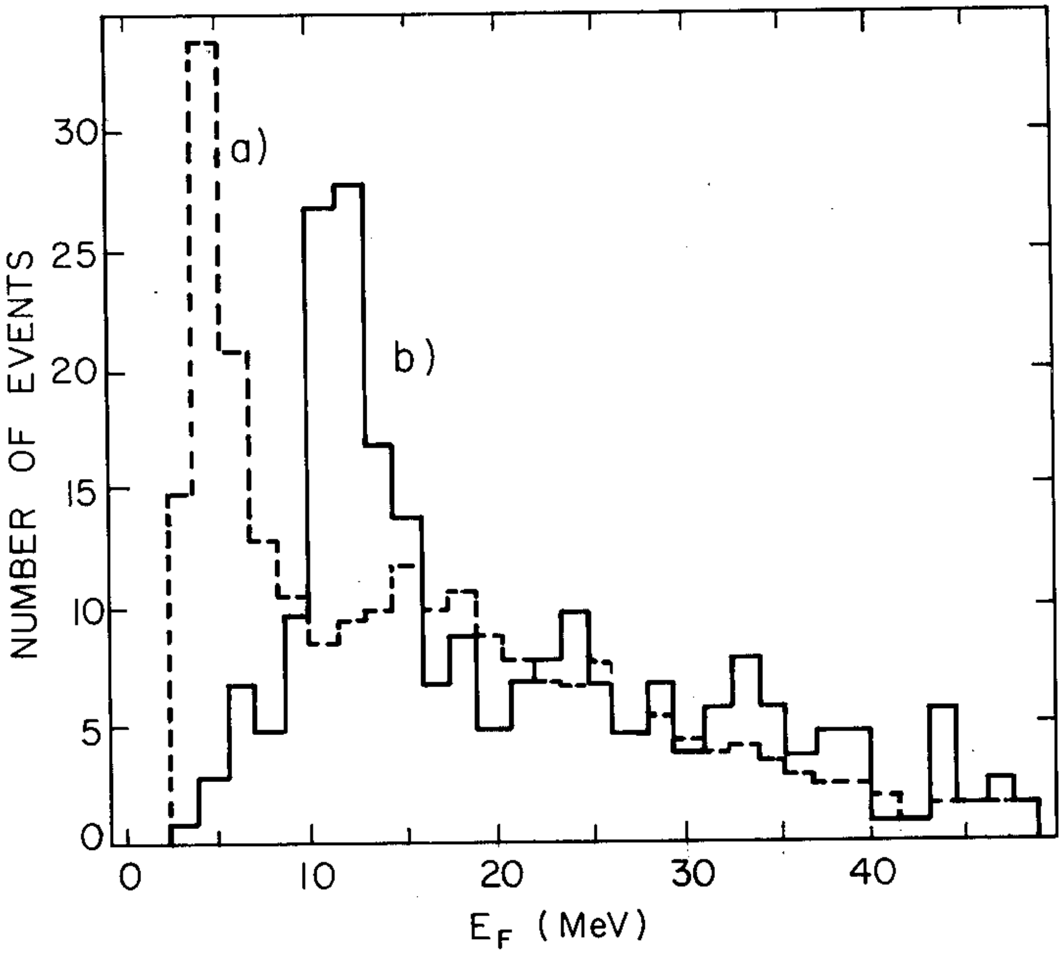


Fig. 2

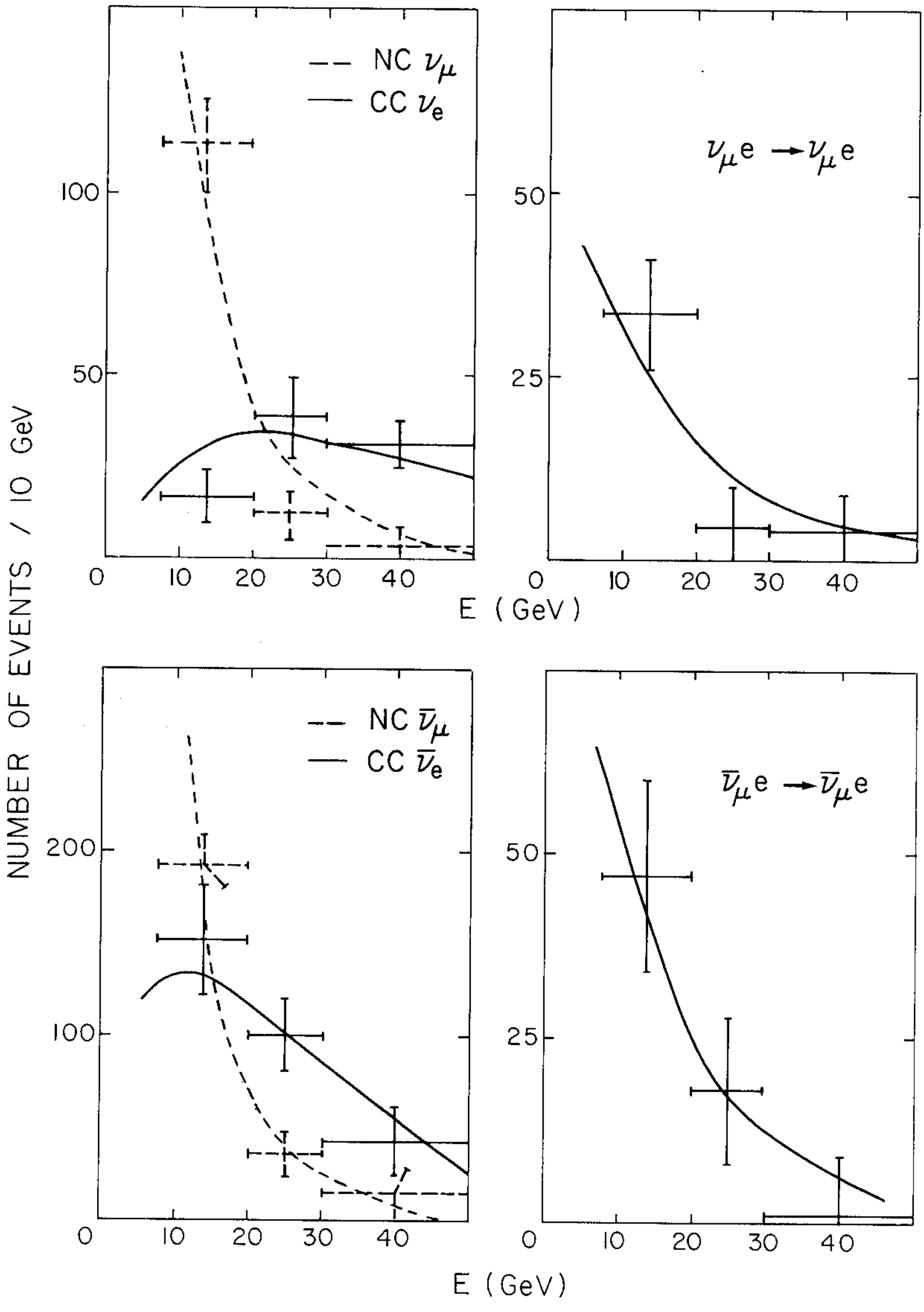
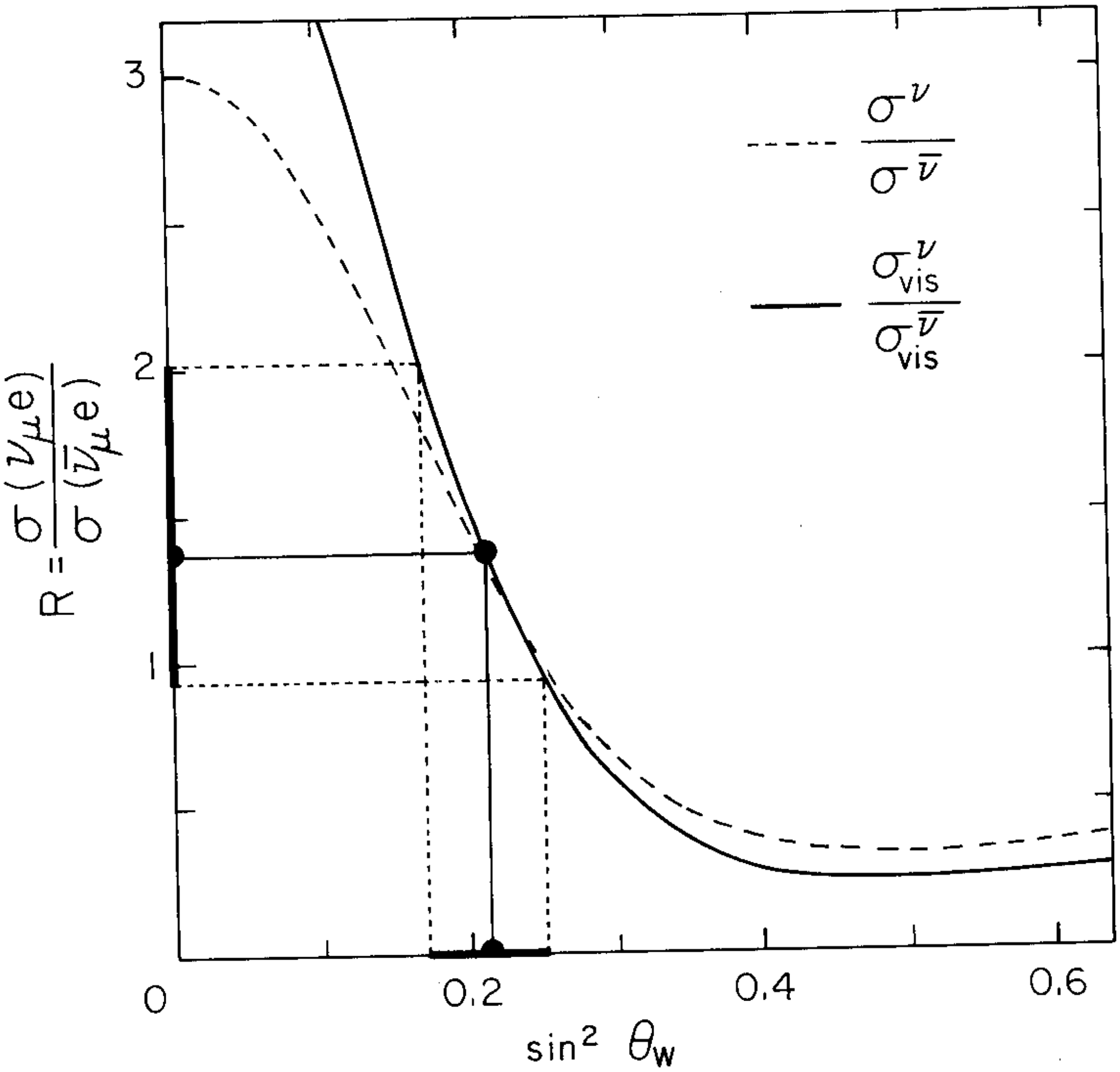

NC ν_μ
CC ν_e
$\nu_\mu e \rightarrow \nu_\mu e$
NC $\bar{\nu}_\mu$
CC $\bar{\nu}_e$
$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
NUMBER OF EVENTS / 10 GeV
E (GeV)
0
10
20
30
40
50
25
100
200

Fig. 3



3
2
1
0
0.2
0.4
0.6
$\sin^2 \theta_W$
$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)}$
$\frac{\sigma^\nu}{\sigma^{\bar{\nu}}}$
$\frac{\sigma^\nu_{vis}}{\sigma^{\bar{\nu}}_{vis}}$

Fig. 4