EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/81-16
9 March 1981

EXPERIMENTAL STUDY OF DIFFERENTIAL CROSS-SECTIONS $d\sigma/dy$ IN NEUTRAL CURRENT NEUTRINO AND ANTINEUTRINO INTERACTIONS

CHARM Collaboration

M. Jonker, J. Panman and F. Udo
NIKHEF, Amsterdam, The Netherlands

J.V. Allaby, U. Amaldi, G. Barbiellini[1], V. Blobel[2], G. Cocconi, W. Flegel, W. Kozanecki[3], K.H. Mess, M. Metcalf, J. Meyer, R.S. Orr, V. Valente[1], A.M. Wetherell and K. Winter
CERN, Geneva, Switzerland

F.W. Büsser, P.D. Gall, H. Grote, B. Kröger, E. Metz, F. Niebergall, K.H. Ranitzsch and P. Stähelin
II. Institut für Experimentalphysik, Universität Hamburg*), Hamburg, Germany

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

A. Baroncelli[4], R. Biancastelli[4], B. Borgia[5], C. Bosio[4], A. Capone[5], F. Ferroni[5], E. Longo[5], P. Monacelli[5], F. de Notaristefani[5], P. Pistilli[5] and C. Santoni[4]
Istituto Nazionale di Fisica Nucleare, Rome, Italy

(Submitted to Physics Letters)

---

1 On leave of absence from the Laboratori Nazionali dell'INFN, Frascati, Italy.

2 Now at II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

3 Now at University of California, Riverside, California, USA.

4 Istituto Superiore di Sanità, Roma, and INFN Sez. Sanità, Rome, Italy.

5 Istituto di Fisica, Università di Roma and INFN Sez. di Roma, Italy.

*) Supported by the Bundesministerium für Forschung und Technologie, Bonn, Fed. Rep. of Germany.

ABSTRACT

We present differential cross-sections $d\sigma/dy$ corrected for resolution and acceptance, for events induced by both the neutral- and charged-current interactions of neutrinos and antineutrinos. They are based on 8553 neutrino and 3578 antineutrino events obtained using the CHARM fine-grain calorimeter in the CERN 200 GeV narrow-band beam. From these differential cross-sections we demonstrate that the coupling strength of the weak neutral current to the strange quark is compatible with being equal to that of the down quark. Assuming this equality we then describe the weak neutral current in terms of one parameter, $\sin^2 \theta$, which we find to be 0.222 ± 0.016. The charged-current differential cross-sections yield values of the fractional momentum-weighted content of the nucleon for non-strange (0.12 ± 0.04) and strange (0.06 ± 0.04) sea quarks.

Furthermore, from the strength of the allowed y^2 term in the neutral-current differential cross-sections we put a limit of 3% on the presence of scalar or pseudoscalar contributions to the weak neutral current. This can alternatively be expressed in terms of the Callan-Gross violation parameter R, where we find $R = 0.10 \pm 0.10$.

We have already reported [1] on the total inclusive cross-sections of neutral-current (NC) and charged-current (CC) events induced by both neutrinos and anti-neutrinos scattering on an isoscalar target ($CaCO_3$), and from these have deduced values of the coupling constants of the neutral weak hadronic current. In this paper we report on the differential cross-section $d\sigma/dy$ determined from the hadron-energy distribution of these events.

Together with a knowledge of the neutrino beam spectrum, the hadron-energy (E_h) distribution of the events allows one to infer the form of the differential cross-section of the events in the inelasticity $y = E_h/E_\nu$. The differential cross-sections for both NC and CC events are directly related to the space-time structure of the weak current involved. They give the admixture of vector (V) and axial-vector (A) couplings and may indicate the presence of any scalar (S) or pseudoscalar (P) terms. In addition, they yield information on the antiquark content, both strange and non-strange, of the nucleon.

Previous experiments [2-5] have investigated the space-time structure of the neutral current by means of the hadron-energy distributions. In this paper we present, for the first time, the acceptance-corrected, resolution-unfolded differential cross-sections $d\sigma/dy$.

The present experiment was performed using the CHARM electronic neutrino detector in the CERN 200 GeV/c narrow-band neutrino beam [6]. Details of the apparatus may be found in another paper [7], and ref. [1] describes the beam layout and monitoring. Briefly, the detector consists of a 180 t marble-scintillator sampling calorimeter. This is surrounded by an iron window-frame magnet, also equipped as a calorimeter, and is followed by a toroidal iron muon spectrometer. Planes of proportional drift tubes measure muon trajectories in the whole apparatus and are used for shower-energy sampling in the iron regions.

The narrow-band beam selects and focuses a momentum band of pions and kaons, produced at 0° by interactions of 400 GeV/c protons on a beryllium target, the central momentum being known to 1%. These parent pions and kaons are allowed to decay in a 300 m long decay tunnel, which is followed by a 410 m long iron and earth shield to range out the decay muons. The two-body decay kinematics of the kaons and pions lead to a dichromatic neutrino-energy spectrum at the detector. In the narrow-band beam there is a well-defined relationship between the neutrino-energy spectrum and the radius of the interaction vertex in the detector, up to an ambiguity caused by the presence of neutrinos from both pion and kaon decays. The neutrino-energy spectrum at a given radius is governed by the production spectra of the secondary kaons and pions, the characteristics of the magnetic focusing channel, and the geometry of the decay tunnel. These parameters are well known [1] and allow one to calculate (via a Monte Carlo calculation) the beam-energy spectrum. Figure 1 shows the beam spectrum calculated for a radius of 80 cm in the CHARM apparatus. In the CHARM detector the interaction vertex of an event is measured with a typical resolution of 3 cm at 50 GeV. This accuracy allows us to fully exploit the energy-radius relationship of the beam.

The data sample comprises those events, with hadron-energy deposition above 4.0 GeV, lying within a fiducial volume chosen to minimize the background of events induced by neutrinos from decays before the momentum slit and to maximize the discrimination between NC and CC events. The numbers of events, before background correction, are given in table 1. The backgrounds for which corrections are needed fall into two general classes, namely event misidentification, leading to confusion between the classes NC and CC, and events induced by the non-narrow-band component of the beam. A full discussion of the event-selection criteria and background evaluations may be found in ref. [1].

For CC events all the initial energy (E_ν) appears as visible energy in the final state, i.e.

$$E_\nu + M = E_\mu + M + E_h \tag{1}$$

and the y value of the event is unambiguously defined by

$$y_{CC} = \frac{E_h}{(E_h + E_\mu)} , \tag{2}$$

where M is the nucleon mass and E_μ the muon energy.

For NC events E_μ is replaced by E'_ν, the outgoing neutrino energy. The latter is obviously not an observable and one must resort to the knowledge of the incoming neutrino-energy spectrum and its radial dependence. Since the neutrino energy for a given event is only known to the level of the inherent beam spread and ambiguity, an unfolding procedure is necessary.

The approach used here was to determine that form of the differential cross-section $d\sigma/dy$ which yielded the best fit to the measured event distribution $d^2N/dE_h dr$ as a function of E_h and the radius r of the interaction point in the detector. Assuming a total cross-section rising linearly with E_ν, then

$$\frac{d^2N}{dE_h dr} = \int F(E_\nu, r) \frac{d\sigma}{dy} dE_\nu \ , \tag{3}$$

where $F(E_\nu, r)$ is the calculated neutrino flux. The differential cross-section $d\sigma/dy$ was parametrized as a linear combination of bell-shaped functions (B-splines), $b_i(y)$:

$$\frac{d\sigma}{dy} = \sum_i a_i b_i(y) \ . \tag{4}$$

The width of the $b_i(y)$ was chosen to be equivalent to a histogram binning of 0.1 in y *). This representation involved no *a priori* assumption concerning the shape of the unfolded differential cross-section, merely that it varies smoothly over an interval in y of the order of the experimental resolution. The unfolding consisted of determining the coefficients a_i in

$$\frac{d^2N}{dE_h dr} = \sum_i a_i \int b_i \left(\frac{E_h}{E_\nu}\right) F(E_\nu, r) \ dE_\nu \tag{5}$$

by a maximum likelihood fit to the experimental distribution, taking into account the magnitude and shape, in E_h and r, of all backgrounds [1]. The integrals over the neutrino flux were numerically evaluated taking account of the experimental resolutions in r and E_h. These integrals can be considered to give the shape of the contribution to $d^2N/dE_h dr$ from each bin in y, while the coefficients a_i give the relative magnitudes of these contributions.

---

*) More specifically the knot distance was chosen to be equal to 0.1. This implies that the $b_i(y)$ cannot represent structures finer than 0.1 in y.

Finally, the value of $d\sigma/dy$, averaged over each bin, was evaluated by integrating the parametrization in eq. (4). The resulting unfolded differential cross-sections for both CC and NC events are shown in figs. 2a and 2b, respectively; the CC distribution incorporates radiative corrections [8]. We emphasize that both the CC and the NC differential cross-sections have been obtained in exactly the same fashion, the primary muon in the CC events being used solely for event classification.

In unfolding a distribution measured with finite resolutions, negative correlations are necessarily introduced between adjacent bins. Representing the distribution by spline functions rather than step functions (a histogram) reduces these correlations. Nevertheless, in fitting a theoretical expression to the unfolded distributions, the complete covariance matrix must be used in calculating the χ^2 *). In fig. 2 the diagonal elements of the covariance matrix have been plotted as "error bars" to give an impression of the statistical uncertainty of each point.

A simple comparison of the shapes of the NC and CC differential cross-sections was first made by parametrizing them as

$$\begin{aligned} \frac{d\sigma^{\nu}}{dy} &= A\{(1-\alpha) + \alpha(1-y)^2\} \\ \frac{d\sigma^{\bar{\nu}}}{dy} &= A\{(\alpha + (1-\alpha)(1-y)^2\} \; . \end{aligned} \tag{6}$$

Fitting the ν and $\bar{\nu}$ differential cross-sections simultaneously yielded the two shape parameters $\alpha^{CC} = 0.16 \pm 0.02$ and $\alpha^{NC} = 0.22 \pm 0.02$. The curves in fig. 2 correspond to these fitted shape parameters.

Assuming a purely V-A charged weak current and that the strange ($s\bar{s}$) sea is negligible, α^{CC} gives the antiquark ($\bar{u},\bar{d}$) content of the nucleon. The value of α^{CC} obtained here is in good agreement with another high-precision determination [9], despite the completely different methods and systematic uncertainties in the two experiments. This agreement confirms the validity of our approach to obtaining the differential cross-sections without using the measured muon momentum in CC

*) The unfolded data points and covariance matrix can be supplied on request.

events, and thus acts as a check on the validity of the results obtained in the same way for the NC events.

Under the assumption that the charged current is purely V-A, the value obtained for α^{NC} indicates that the neutral current is also predominantly V-A.

Within the context of the quark parton model, and under the assumption that the weak currents contain only V and A parts, the differential cross-sections $d\sigma/dy$ for deep inelastic scattering can be written in more detail [10] as

$$\begin{aligned}
\frac{d\sigma^{\nu}}{dy}\,(CC) &= B\{(1-\alpha^{\nu}) + \alpha^{\nu}(1-y)^2\} \\
\frac{d\sigma^{\bar{\nu}}}{dy}\,(CC) &= B\{\alpha^{\bar{\nu}} + (1-\alpha^{\bar{\nu}})(1-y)^2\} \\
\frac{d\sigma^{\nu(\bar{\nu})}}{dy}\,(NC) &= B\{g^2_{L(R)}[(1-\alpha^{\bar{\nu}}) + \alpha^{\nu}(1-y)^2] \\
&\quad + g^2_{R(L)}[\alpha^{\nu} + (1-\alpha^{\bar{\nu}})(1-y)^2] \\
&\quad + g^2_S(\alpha^{\bar{\nu}} - \alpha^{\nu})[1 + (1-y)^2]\}\ ,
\end{aligned} \tag{7}$$

where B is a normalization constant.

The quark structure of the nucleon is described by α^{ν} and $\alpha^{\bar{\nu}}$; for example $\alpha^{\bar{\nu}} - \alpha^{\nu}$ is the fractional momentum-weighted strange quark-antiquark content and α^{ν} is the non-strange antiquark content. The constants g^2_L and g^2_R are the left-handed and right-handed couplings of the weak neutral current to "up" and "down" quarks, while g^2_S is the sum of the right- and left-handed couplings to "strange" quarks.

By simultaneously fitting these more detailed expressions to the four unfolded differential cross-sections we have extracted the right- and left-handed couplings of the weak neutral current; the resulting fitted parameters are given in table 2.

The values of g^2_L and g^2_R obtained by neglecting the terms in g^2_S (fit A) are consistent with the values obtained from the cross-sections alone [1]. This confirms that the shapes of the differential cross-sections are consistent with the amount of right-handed coupling required by the cross-section ratios. The amount of strange quark-antiquark sea $(\alpha^{\bar{\nu}} - \alpha^{\nu}) = 0.086 \pm 0.058$ is consistent with that found in charm-changing reactions [11].

The form of the NC y distribution in eq. (7) precludes the possibility of varying all five parameters α^{ν}, $\alpha^{\bar{\nu}}$, g_L^2, g_R^2, and g_S^2 simultaneously in a fit. In particular the error on g_S^2 is strongly correlated with the value of $(\alpha^{\bar{\nu}} - \alpha^{\nu})$. This can be understood from the last term in eq. (7), where g_S^2 becomes undefined as $(\alpha^{\bar{\nu}} - \alpha^{\nu})$ tends to zero. In fit A the value of $(\alpha^{\bar{\nu}} - \alpha^{\nu})$ is determined almost completely by the CC data alone; omitting the NC data from the fit yields $(\alpha^{\bar{\nu}} - \alpha^{\nu}) = 0.086 \pm 0.050$. In extracting g_S^2 we have thus constrained $(\alpha^{\bar{\nu}} - \alpha^{\nu}) = 0.086 \pm 0.050$. Furthermore, the model-independent analysis of ref. [1] indicates that g_L^2 and g_R^2 are, within the context of the Glashow-Salam-Weinberg model, consistent with being functions of only one parameter, the electroweak mixing angle. Fit B (see table 2) has $\alpha^{\bar{\nu}}$, $\sin^2\theta$, and g_S^2 as free parameters and $(\alpha^{\bar{\nu}} - \alpha^{\nu})$ constrained. The fitted over-all neutral-current coupling of the strange quark is $g_S^2 = 0.26 \pm 0.06$, and the fitted value of the electroweak mixing angle is $\sin^2\theta = 0.23 \pm 0.02$. From the value of $\sin^2\theta$, one can calculate the over-all right- and left-handed neutral-current coupling of the down quark g_d^2, which is analogous to g_S^2; then

$$\frac{g_S^2}{g_d^2} = 1.39 \pm 0.43 \ ,$$

where the error includes systematic effects. The domain of g_S^2 and $\sin^2\theta$ allowed by this fit, in which the strange sea is constrained to be in the region favoured by our CC data alone, is shown in fig. 3. The relationship between these parameters in the model is also shown.

Thus we find that the total coupling strength of the weak neutral current to the strange quark is consistent with being equal to that of the down quark, an assumption implied by the GIM mechanism [12].

Motivated by this result, we go on to assume that the couplings of the u, d, and s quarks can all be described in terms of the Glashow-Salam-Weinberg prescription. The neutral-current sector is then described by a single parameter, $\sin^2\theta$. The fit (fit C) gives $\sin^2\theta = 0.222 \pm 0.016$, and $(\alpha^{\bar{\nu}} - \alpha^{\nu}) = 0.06 \pm 0.04$. These two numbers give the best description of our data within the context of the Glashow-Salam-Weinberg model of the weak current, and the scaling quark parton model of the nucleon.

In the preceding we have first demonstrated the existence of a right-handed part in the neutral current, independent of the validity of the Glashow-Salam-Weinberg model. After showing that the neutral-current coupling of the strange quark is consistent with being equal to that of the down quark, we have then described the neutral-current sector completely in terms of the Glashow-Salam-Weinberg model. This, of course, already assumes the presence of only V and A currents. However, if there were a scalar (S) or pseudoscalar (P) contribution to the neutral current, it would contribute equally to neutrino and antineutrino interactions, and would manifest itself, in the differential cross-sections, as a term proportional to y^2.

We thus parametrize the NC differential cross-sections as

$$\frac{d\sigma^{\nu}}{dy}(\mathrm{NC}) = A\{(1-\alpha) + \alpha(1-y)^2\} + By^2$$
$$\frac{d\sigma^{\bar{\nu}}}{dy}(\mathrm{NC}) = A\{\alpha + (1-\alpha)(1-y)^2\} + By^2 \ . \qquad (8)$$

Then the ratio B/A gives the relative proportions of S and/or P and V,A. A simultaneous fit of eq. (8) to the two NC differential cross-sections gives $B/A = -0.05 \pm 0.05$, implying

$$\frac{g^2_{SP}}{g^2_{VA}} \leq 0.03 \text{ at the 95\% confidence level ,}$$

where g^2_{SP} and g^2_{VA} are the SP and VA total coupling strengths.

This represents a considerable improvement upon the previously published limits [2-5]. The analysis in this form disregards the possibility of a conspiracy of SPT terms mimicking a V,A structure in the neutral currents [13,14]. This ambiguity has, however, already been resolved in the case of charged currents [15].

A term in y^2 could be induced independently of the presence of SP terms. The naive quark model, with free spin ½ quarks, predicts the Callan-Gross relation $2xF_1(x) = F_2(x)$. A violation of this equality, as expected by quantum chromodynamics (QCD), would also manifest itself as a term in y^2 in the NC differential cross-sections. Defining

$$R = \frac{F_2(x) - 2xF_1(x)}{F_2(x)} \ ,$$

from eq. (8) we may make the identification

$$R = \frac{-2B}{A} ,$$

and from the same fit we obtain

$$R = 0.10 \pm 0.10 ,$$

in agreement with results obtained from CC events by other experiments [9,16,17]. This evaluation, using NC events, has the advantage of not being affected by radiative corrections, which play a major role in the analysis of CC events.

In conclusion, we have presented, for the first time, differential cross-sections $d\sigma/dy$ corrected for resolution and acceptance for both NC and CC events induced by neutrinos and antineutrinos on an isoscalar target. The CC differential cross-sections were obtained without use of the muon momentum, and their compatibility with other experiments serves to confirm the validity of the method when applied to NC events.

Within the context of the Glashow-Salam-Weinberg model the weak neutral-current coupling to the s quark was found to be equal to that of the d quark. This justified a fit to our data, taking into account s quarks, in which the neutral-current sector was described solely in terms of $\sin^2 \theta$. This fit yielded $\sin^2 \theta = 0.222 \pm 0.016$. The same fit yielded non-strange and strange nucleon sea quark contents of 0.12 ± 0.04 and 0.06 ± 0.04.

Finally, the NC differential cross-sections seem to allow only a very small contribution from S and P terms.

Acknowledgements

We most sincerely thank our many technical collaborators, the members of the SPS staff for the excellent operation of the accelerator, and G. Cavallari, H. Heyne, J. May, G. Sigurdsson and G. Stefanini for their competent help with the beam monitoring. We gratefully acknowledge the work of C. Busi on data reduction and analysis, and the part played by F. Schneider in building and operating the apparatus.

REFERENCES

[1] M. Jonker et al., CHARM Collaboration, Phys. Lett. 99B (1981) 265.

[2] M. Holder et al., Phys. Lett. 72B (1977) 254.

[3] P. Wanderer et al., Phys. Rev. D 17 (1978) 1679.

[4] F.S. Merritt et al., Phys. Rev. D 17 (1978) 2199.

[5] H. Deden et al., Nucl. Phys. B149 (1979) 1.

[6] J.V. Allaby et al., CERN/SPSC/113-7; SPC/345 (1977).

[7] A.N. Diddens et al., CHARM Collaboration, Nucl. Instrum. Methods 178 (1980) 27.

[8] A. de Rũjula et al., Nucl. Phys. B154 (1979) 394.

[9] J.G.H. de Groot et al., Z. Phys. C 1 (1979) 143.

[10] L.M. Sehgal, Proc. Int. Neutrino Conf., Purdue Univ., West Lafayette, Indiana, 1978 (ed. E.C. Fowler) (Purdue Univ., West Lafayette, Indiana, 1978), p. 263.

[11] H. Abramowicz et al., CDHS Collaboration, Contribution to 20th Int. Conf. on High Energy Physics, Madison, USA, 1980.

[12] S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2 (1970) 1285.

[13] B. Kayser et al., Phys. Lett. 52B (1974) 385.

[14] R.L. Kingsley et al., Phys. Rev. D 10 (1974) 2216.

[15] M. Jonker et al., CHARM Collaboration, Phys. Lett. 86B (1979) 229.

[16] P.C. Bosetti et al., Phys. Lett. 70B (1977) 273.

[17] A. Bodek et al., SLAC-PUB-2248 (1979).

Table 1

Raw event numbers with shower energy > 4 GeV
(before background corrections)

	Charged current	Neutral current
ν	6271	2282
$\bar{\nu}$	2536	1042

Table 2

Results of simultaneous fits to all y distributions.
Errors include systematic effects.

	Fit A	Fit B	Fit C
α^{ν}	0.10 ± 0.05	b)	0.12 ± 0.04
$\alpha^{\bar{\nu}}$	0.18 ± 0.02	0.18 ± 0.02	0.18 ± 0.02
g_L^2	0.32 ± 0.02	calculated from $\sin^2\theta$	calculated from $\sin^2\theta$
g_R^2	0.05 ± 0.02	calculated from $\sin^2\theta$	calculated from $\sin^2\theta$
g_S^2	0 a)	0.26 ± 0.06	calculated from $\sin^2\theta$
$\sin^2\theta$	-	0.23 ± 0.02	0.222 ± 0.016

a) Value fixed in fit.

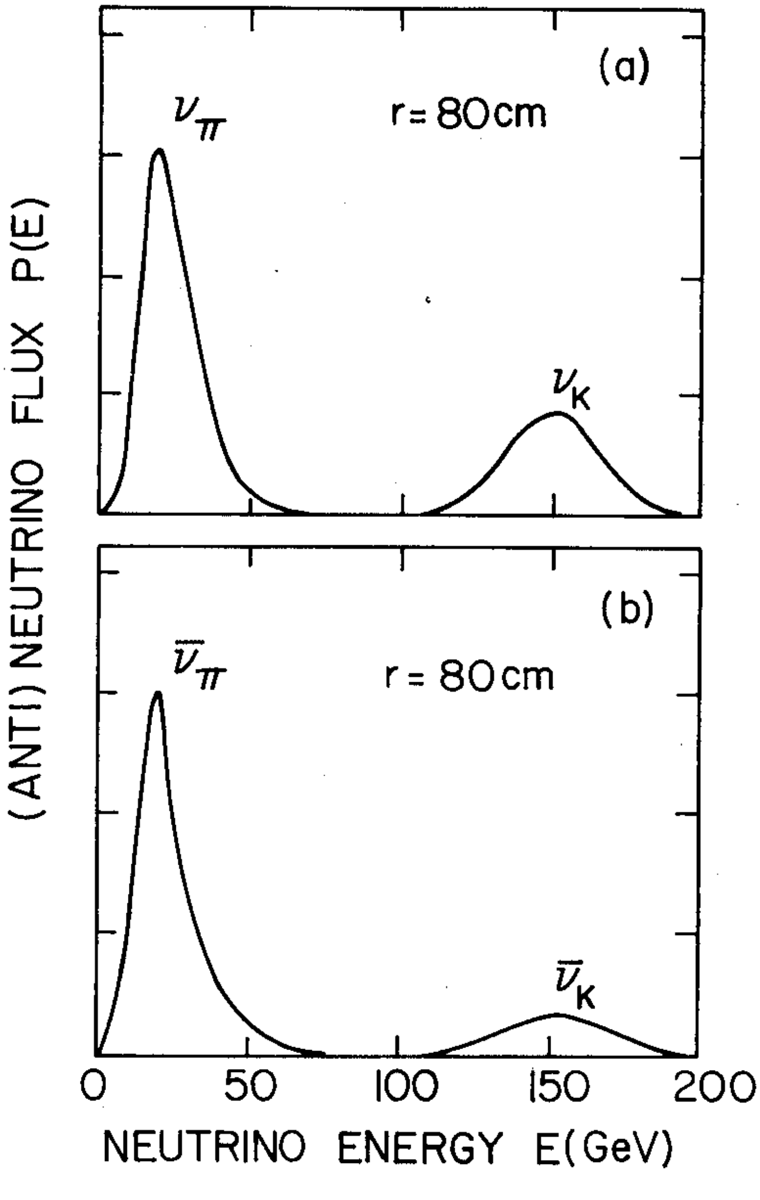
b) $(\alpha^{\bar{\nu}} - \alpha^{\nu})$ constrained to 0.086 ± 0.050.

Figure captions

Fig. 1 : The calculated neutrino and antineutrino fluxes, as a function of neutrino energy, at a radius of 80 cm in the CHARM detector.

Fig. 2 : The differential cross-section, $d\sigma/dy$, after resolution unfolding and acceptance correction. The curves correspond to the two-parameter fit of eq. (6) described in the text: a) CC events; b) NC events.

Fig. 3 : The allowed domain of g_S^2 and $\sin^2 \theta$, with $(\alpha^{\bar{\nu}} - \alpha^{\nu})$ constrained to 0.086 ± 0.050, in fit B. The 1σ and 2σ contours are statistical only. The dotted line is the expected relationship in the Glashow-Salam-Weinberg model.



(a)
ν_π
r = 80cm
ν_K
(b)
$\bar{\nu}_\pi$
r = 80cm
$\bar{\nu}_K$
(ANTI) NEUTRINO FLUX P(E)
0
50
100
150
200
NEUTRINO ENERGY E(GeV)

Fig. 1

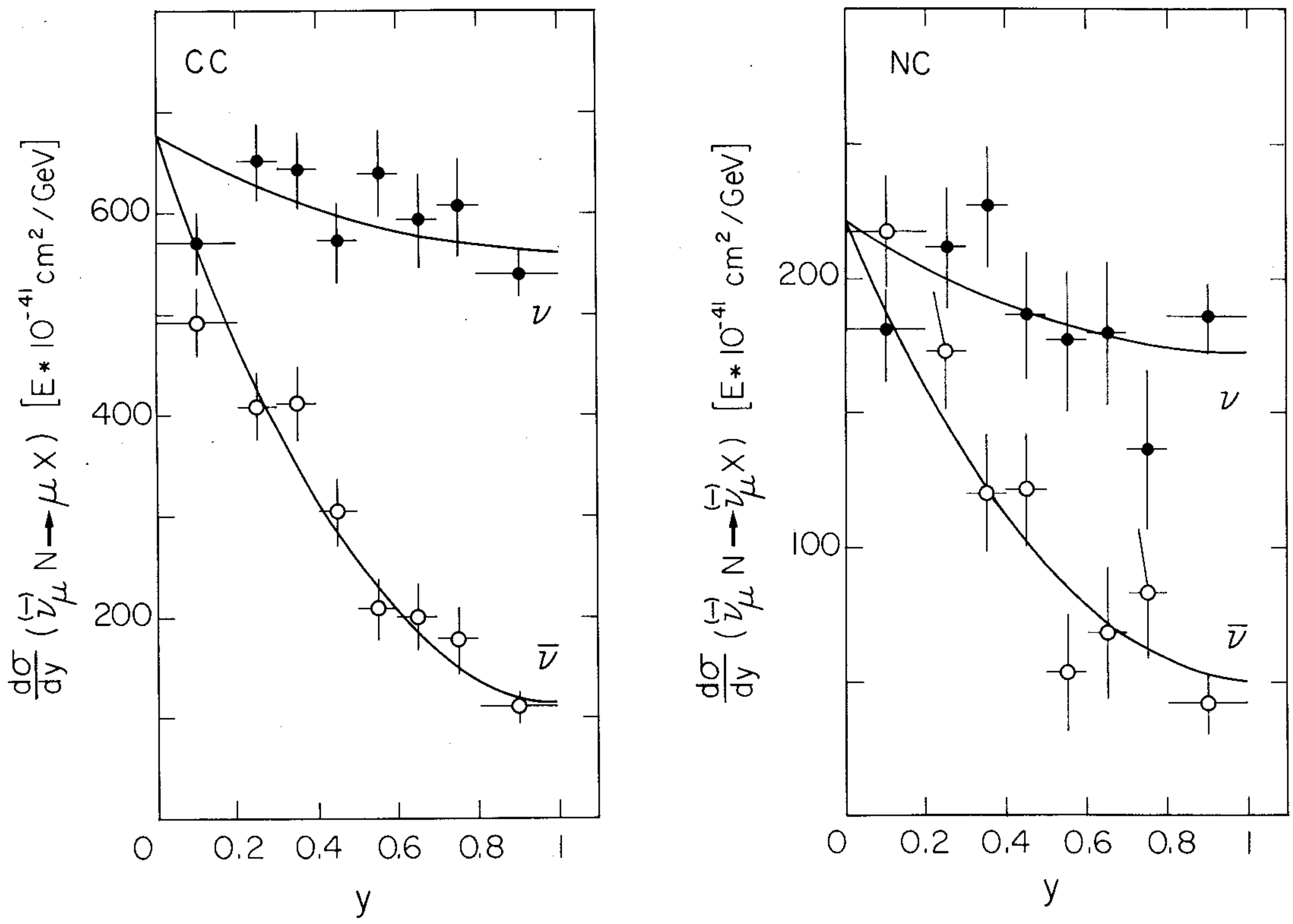

CC
NC
$\frac{d\sigma}{dy}(\overset{(-)}{\nu}_{\mu} N \rightarrow \mu X)$ [E * 10^{-41} cm^2/GeV]
$\frac{d\sigma}{dy}(\overset{(-)}{\nu}_{\mu} N \rightarrow \overset{(-)}{\nu}_{\mu} X)$ [E * 10^{-41} cm^2/GeV]
ν
$\bar{\nu}$
600
400
200
100
0
0.2
0.4
0.6
0.8
1
y

Fig. 2

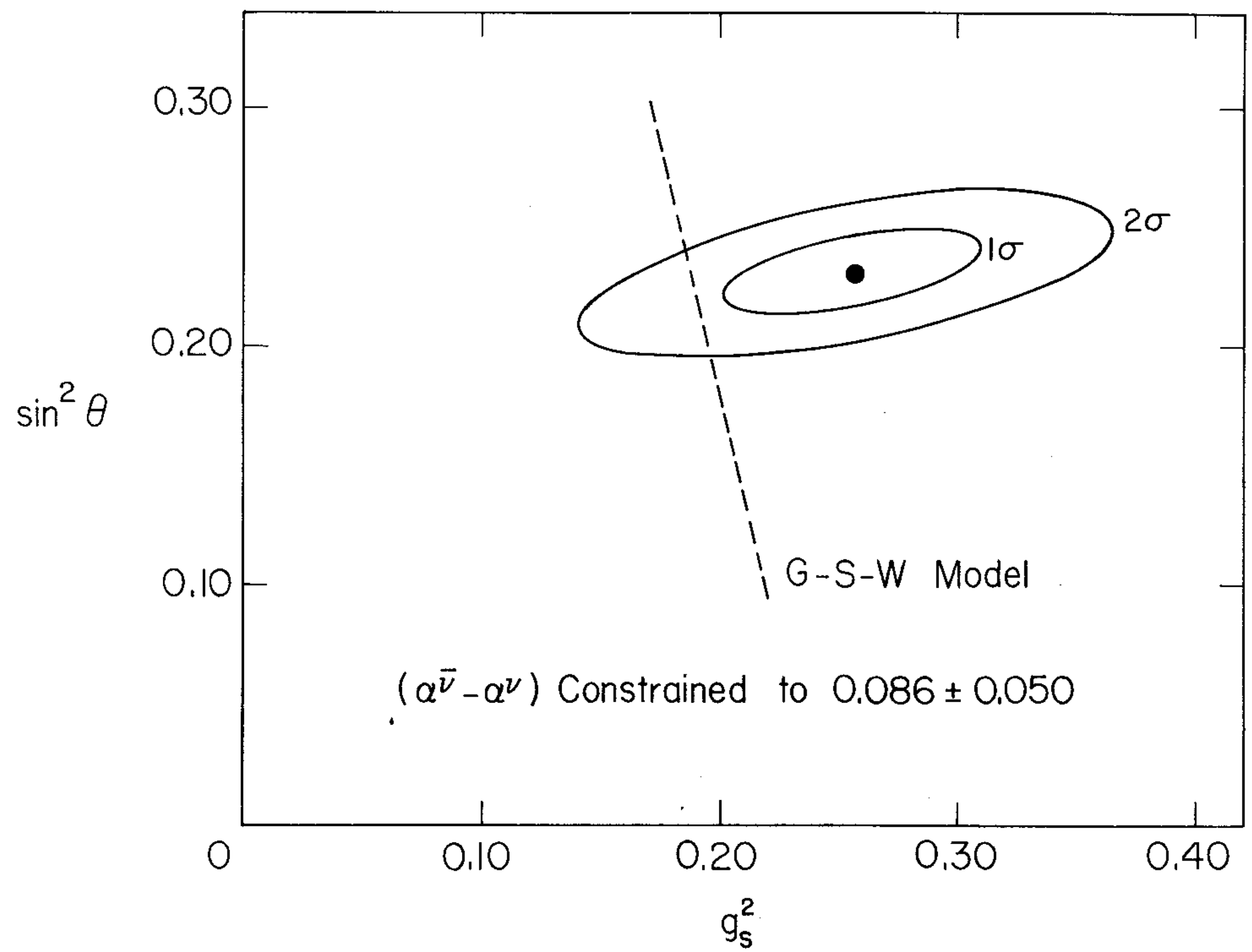

2σ
1σ
G-S-W Model
(α$\bar{\nu}$ - αν) Constrained to 0.086 ± 0.050
0.30
0.20
0.10
0
0.10
0.20
0.30
0.40
$\sin^2\theta$
g_s^2

Fig. 3