SOME RECENT EXPERIMENTAL RESULTS IN HIGH-ENERGY NEUTRINO PHYSICS

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1. INTRODUCTION

High-energy neutrino experiments can be expected to give important insight into both the structure of hadronic matter (because of the point-like nature of the collisions, or the equivalent statement, the high mass of the intermediate boson, if it exists), and also into the structure of the weak interactions. Among the more striking past results have been a) the discovery that there must be at least two neutrinos¹⁾; b) the discovery of neutral weak currents²⁾; c) the demonstration that, at least at relative low energies, scaling and the quark parton models are reasonable approximations; and d) the discovery of dileptons and their probable association with a new family of particles^{3, 4)}.

In the last two years another very important development has been the discovery of large scaling violations in the y -distribution of antineutrino charged current reactions, in the change in this y -distribution with neutrino energy, and in the energy dependence of the ratio of charged current antineutrino to neutrino total cross-sections. These results, due mainly to the Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF) Collaboration at FNAL and in some measure confirmed by the California Institute of Technology (CIT) group, have been collectively called the "high- y anomaly".

In the last half year the new Super Proton Synchrotron (SPS) accelerator has been in operation, and the results collected here are the first results obtained there, although other new results, where available, are also included. The following subjects are discussed:

- a) the SPS narrow band neutrino beam and CERN-Dortmund-Heidelberg-Saclay (CDHS) electronic detector;
- b) charged current interactions and the "high- y anomaly";
- c) neutral current interactions and the Weinberg-Salam model;
- d) dilepton production and charm;
- e) "wrong-sign" muons, charm-changing neutral currents and the charmed sea;
- f) the x -distributions of the u , d , and s quark seas.

2. THE SPS NARROW-BAND NEUTRINO BEAM AND THE CDHS DETECTOR

The neutrino experimental facilities at CERN are as follows:

- a) A beam hall in which the hadron beams, produced by protons on a target, are formed. Two such beams are at present installed and can be used alternately: a "wide-band" horn focused beam and a "narrow-band" momentum selected beam. The beam hall is 120 m long from the proton target to the end.

- b) An evacuated decay tunnel 300 m long.
- c) A shield, made chiefly of iron, to absorb hadrons and muons.
- d) Devices to monitor the absolute beam flux and the beam composition.
- e) The neutrino interaction detector.

The over-all layout is shown in Fig. 1.

Until now, only the narrow-band beam has been used. In this beam secondary hadrons are focused on a momentum slit and then made as nearly parallel as possible (see Fig. 2). Some of the parameters of the CERN beam are:

maximum hadron momentum:	275 GeV
acceptance, solid angle:	10 μ sr
momentum resolution:	$\Delta p/p = \pm 5\%$
angular divergence:	0.2 mrad

Since the neutrinos are dominantly ($\sim 98\%$) produced in the two-body decays $\pi \rightarrow \mu + \nu$ and $K \rightarrow \mu + \nu$, the neutrino momentum can be determined for each event from the decay kinematics (see Fig. 3), subject to the double valued π -K ambiguity. Because of the low π - μ mass difference, the pion neutrinos are less energetic. Some data from the CDHS experiment are shown in Figs. 4 and 5 to illustrate the kinematics. The uncertainty in the neutrino energy varies with decay angle (detector radius) from $\sim 5\%$ at $r = 0$ to $\sim 20\%$ for $r = r_{\text{max}} = 1.8$ m, for kaon neutrinos at a hadron beam energy of 200 GeV. The resolution is much worse for pion neutrinos. At the SPS the entire neutrino spectrum, from quite low energies due to pion neutrinos up to the highest energies from kaon neutrinos, is covered for one setting of the hadron beam energy. This can be seen in Fig. 6, where the wide-band and "effective" narrow-band spectra for the CDHS detector are shown.

The beam monitoring devices are the following:

- a) a beam current transformer (BCT), with accurate absolute calibration, which measures the absolute hadron flux and is placed immediately following the beam-forming elements;
- b) a Čerenkov counter capable of separating π 's, K's, and protons, placed just after the BCT and in front of the decay tunnel;
- c) a monitor calorimeter just in front of the shield, in which the energy of the hadron beam is largely converted into heat so that the total hadron flux can be measured;
- d) solid-state detectors placed in pits at various depths in the shield, to sample the muon flux; these detectors are intercalibrated, and an absolute calibration is obtained in a hadron beam by means of track counting in nuclear emulsions;

- e) various ionization and secondary emission chambers to monitor the beam positions and focusing properties.

The three absolute monitors at present agree (disagree) to $\sim \pm 10\%$. The uncertainties in the K/π ratios are also 5-10% at present. It is hoped that these uncertainties will diminish with time.

An over-all view of the CDHS detector⁵⁾ is shown in Fig. 7. It is composed of 19 magnetized iron modules and triple plane drift chambers. Each of these modules combines the functions of neutrino target, hadron shower detector, and muon spectrometer. Each is composed of iron plates 3.75 m in diameter, with an iron thickness of 75 cm, corresponding to a target weight of 65 tons. The iron is magnetized with $\sim 20,000$ ampere turns to have a toroidal field, which falls from ~ 20 kG at 15 cm radius to ~ 16 kG at the outer edge. The first seven of these modules are made of fifteen 5 cm plates, the last twelve of five 15 cm thick plates. Between each pair of plates is a layer of eight scintillator strips viewed from both sides. The ratio of right to left pulse-height serves to measure the horizontal position of the shower, and the sum of right and left pulse-heights, after correction for attenuation using the position measurement, is used to measure the hadron shower energy calorimetrically. The accuracy of horizontal and vertical position measurement is at present ~ 15 -20 cm. No information on the shower direction is obtained. The energy of electrons and photons which may be produced in neutrino reactions is included in the measured hadron shower energy.

The response of these calorimeters to hadrons and electrons of several energies has been measured⁶⁾ in a smaller, magnetized iron, test calorimeter (60 cm $\times$ 80 cm sensitive area, 150 cm long), which uses the same scintillator, phototubes, and electronic circuits as the larger detector. Some of the results are shown in Figs. 8 and 9. The resolution for hadrons is reasonably described by the formula $\Delta E_h/E_h = 0.8/\sqrt{E_h}$ (GeV) for 5 cm sampling. For electron (photon) showers it is better by a factor of two. For the 15 cm sampling, the resolution is measured to be poorer by a factor of $\sqrt{3}$.

The calibration of the phototubes and pulse-height circuits is accomplished on the basis of cosmic-ray muon events which are recorded between machine bursts.

The response of the muon spectrometer has not been calibrated. It is deduced from the measured magnetization and the calculated multiple scattering and known drift chamber measurement errors. The momentum resolution is ± 7 to $\pm 15\%$, depending on track length, and the absolute error should not exceed 1-2%.

3. INCLUSIVE CHARGED NEUTRINO SCATTERING AND THE "HIGH-y ANOMALY"

3.1 Kinematics and quark-parton model

We begin by recalling some of the underlying kinematical and theoretical notions:

The incident neutrino of momentum k , energy E_ν , collides with a hadron of momentum p to produce a final lepton of momentum k' at laboratory angle θ , and the hadronic state p' , with energy E_h , and mass W .

$$S \equiv (k + p)^2 \approx 2E_\nu M$$

$$Q^2 \equiv -(k - k')^2 = 4E_\mu E_\nu \sin^2 \theta/2$$

$$\nu \equiv p \cdot q \approx ME_h$$

$$W = \sqrt{2\nu - Q^2}$$

$$x \equiv Q^2/2\nu \approx 2E_\nu E_\ell \sin^2 \frac{\theta}{2} / ME_h; \quad 0 \leq x \leq 1.$$

$$y \equiv \nu/k \cdot p \approx E_h/E_\nu = \text{inelasticity}; \quad 0 \leq y \leq 1.$$

The inclusive process will be described by the variables x , y , and E_ν . Some contours for fixed laboratory lepton angle and W are shown in Fig. 10 in the x - y plot and, for comparison, in the Q^2 - ν plot.

We continue by recalling some results of neutrino V,A theory and the quark parton model⁷⁾. If the weak interaction is describable by V and A currents, and if polarization effects can be ignored, the inclusive differential cross-sections are described by three form factors that are functions of Q^2 and ν :

$$\frac{d^2\sigma_{\nu,\bar{\nu}}}{dQ^2 dv} = \frac{G^2}{2\pi M} \frac{E_\ell}{E_\nu} \left[\cos^2 \frac{\theta}{2} W_2(Q^2, \nu) + 2 \sin^2 \frac{\theta}{2} W_1(Q^2, \nu) + \frac{(E_\nu + E_\ell)}{M} \sin^2 \frac{\theta}{2} W_3(Q^2, \nu) \right].$$

At high energy and momentum transfer, if there are no high mass thresholds, scaling must be expected, and the form factors can be written in terms of the unique variable x :

$$F_1(x) = W_1(Q^2, \nu)$$

$$F_2(x) = \nu W_2(Q^2, \nu)$$

$$F_3(x) = \nu W_3(Q^2, \nu),$$

and

$$\frac{d\sigma_{\nu,\bar{\nu}}}{dx dy} = \frac{G^2 M E_\nu}{\pi} \left[(1-y)F_2 + xy^2 F_1 + (y - y^2/2) \times F_3 \right].$$

The main consequences of scaling are

- i) the cross-sections are proportional to the neutrino energy; and
- ii) the x - and y -dependences are independent of neutrino energy.

In the quark-parton model, the cross-section is assumed to be the incoherent sum of the scattering on almost free quark constituents of the nucleon. Then

$$d^2\sigma/dxdy = \sum_j f_j(x) d\sigma_j/dy,$$

where $f_j(x)$ is the distribution in the fractional nucleon momentum carried by quarks of type j , and $d\sigma_j/dy$ the neutrino cross-section of the j -type quark. Some examples of these elementary cross-sections in the G.I.M. ⁸⁾ model are listed in Table 1.

Table 1

Neutrino quark cross-sections

Process	$d\sigma/dy$ in units of $G^2 M E_\nu / \pi$
* $\nu + d \rightarrow \mu^- + u$	$2 \times \cos^2 \theta_c$
$\nu + s \rightarrow \mu^- + u$	$2 \times \sin^2 \theta_c$
$\nu + s \rightarrow \mu^- + c$	$2 \times \cos^2 \theta_c$
* $\nu + d \rightarrow \mu^- + c$	$2 \times \sin^2 \theta_c$
$\nu + \bar{u} \rightarrow \mu^- + \bar{d}$	$2 \times \cos^2 \theta_c (1-y)^2$
$\nu + \bar{u} \rightarrow \mu^- + \bar{s}$	$2 \times \sin^2 \theta_c (1-y)^2$
* $\bar{\nu} + u \rightarrow \mu^+ + d$	$2 \times \cos^2 \theta_c (1-y)^2$
* $\bar{\nu} + u \rightarrow \mu^+ + s$	$2 \times \sin^2 \theta_c (1-y)^2$
$\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{c}$	$2 \times \cos^2 \theta_c$
$\bar{\nu} + \bar{d} \rightarrow \mu^+ + \bar{c}$	$2 \times \sin^2 \theta_c$
$\bar{\nu} + \bar{d} \rightarrow \mu^+ + \bar{u}$	$2 \times \cos^2 \theta_c$
$\bar{\nu} + \bar{s} \rightarrow \mu^+ + \bar{u}$	$2 \times \sin^2 \theta_c$

The collisions dominated by "valence" quarks are marked *. All others proceed via "sea" quarks.

It follows in this model that

$$2xF_1 = F_2 = \frac{18}{5} F^{e,d} = q + \bar{q}$$

$$-xF_3 = q - \bar{q} ;$$

where

$$q \equiv x[u(x) + d(x) + s(x) + c(x)] = (F_2 - xF_3)/2 ,$$

$$\bar{q} \equiv x[\bar{u}(x) + \bar{d}(x) + \bar{s}(x) + \bar{c}(x)] = (F_2 + xF_3)/2 .$$

$u(x)$, $d(x)$, $s(x)$, and $c(x)$ are the distributions, in the fractional momentum of the proton, of up, down, strange, and charmed quarks, respectively, and $F^{ed}(x)$ is the structure function measured in electron-deuteron collisions.

Then

$$\frac{d^2\sigma_{\nu}}{dx dy} = \frac{G^2 ME_{\nu}}{\pi} \left[q + \bar{q}(1-y)^2 \right]$$

and

$$\frac{d^2\sigma_{\bar{\nu}}}{dx dy} = \frac{G^2 ME_{\nu}}{\pi} \left[q(1-y)^2 + \bar{q} \right]$$

These expressions separate very clearly the effect of left-handed hadronic currents, the terms in q , and right-handed hadronic currents, the terms in $\bar{q}$. The q term is composed of the "valence" contribution $q - \bar{q}$, which is supposed to dominate, and the "sea" distribution $\bar{q}$, which is supposed to be less important. The $\bar{q}$ term is pure "sea".

In terms of the fractional contribution of the valence quarks,

$$B \equiv \frac{\int (q(x) - \bar{q}(x)) dx}{\int (q(x) + \bar{q}(x)) dx},$$

the y -dependences of the cross-sections are

$$d\sigma_{\nu}/dy \propto (1+B) + (1-B)(1-y)^2$$

and

$$d\sigma_{\bar{\nu}}/dy \propto (1+B)(1-y)^2 + (1-B)$$

$$R \equiv \sigma_{\bar{\nu}}/\sigma_{\nu} = (4-2B)/(4+2B).$$

If the sea is negligibly small,

$$B = 1, \quad R = 1/3, \quad \langle y_{\nu} \rangle = 1/2, \quad \text{and} \quad \langle y_{\bar{\nu}} \rangle = 1/4.$$

3.2 Summary of the experimental situation up to 1975

In Figs. 11-13 some results of the Gargamelle and earlier FNAL experiments, in particular x -distributions⁹⁾, y -distributions¹⁰⁾ and total cross-sections as a function of the neutrino energy¹¹⁻¹³⁾, are shown.

The data are all in good agreement with the simple quark parton model, within rather large errors.

3.3 The "high- y anomaly"

The experimental results, dominantly due to the HPWF Collaboration at FNAL, and to some extent confirmed by the CIT group, are shown in Figs. 14-18. The anomalous behaviour consists of the following elements:

- i) a flat y -distribution for antineutrinos at $x < 0.1$ ¹⁴⁾ (Fig. 14);
- ii) an increase with energy in $\langle y \rangle$ for antineutrinos (Figs. 15 and 16), equivalent to a reduction in the B parameter with energy (Fig. 17) ¹⁵⁻¹⁷⁾.
- iii) an increase with energy in the total cross-section ratio $\sigma_{\bar{\nu}}/\sigma_{\nu}$ (Fig. 18) ¹⁸⁾.

These results generated great interest because of the far-reaching implications. They were interpreted by the HPWF group, on the one hand to show violation of the charge independence which predicts approximate equality of neutrino and antineutrino cross-sections at small y , and on the other hand as showing the existence of a new type of quark of mass approximately 5-7 GeV, and which is produced by antineutrinos through a right-handed current. In this way the "threshold" at ~ 40 GeV, the increase in $\sigma_{\bar{\nu}}/\sigma_{\nu}$ with energy, and the increase in $\langle y \rangle$ with energy could be understood.

3.4 Results of the CDHS Collaboration ^{*)} on the high- y anomaly ¹⁹⁾

We have analysed data obtained in 200 GeV narrow-band neutrino and antineutrino beams to check these results. The acceptance of this apparatus extends to higher y (see Fig. 19), and the event numbers are ~ 5 -10 times larger than those of the previous samples, so that both systematically as well as statistically the data are substantially superior. The energy distributions for the two samples are shown in Fig. 20. In Fig. 21 the data are shown which should be compared with Fig. 14. In particular it should be noted that the y -distribution at small x is very far from uniform, but shows, in addition to the dominant $(1-y)^2$ distribution, about 25% uniform contribution, not inconsistent with what can be expected from the antiquark sea at such small x . In Fig. 21, the antineutrino and neutrino distributions have been normalized to the same incident neutrino flux so that the cross-sections can be compared at small y to check charge independence. No deviation outside of the $\sim 10\%$ relative flux normalization uncertainty is observed.

The data relevant to the observed change in antineutrino y -distribution and B parameter with energy are shown in Figs. 22-24. We follow HPWF in applying the cut $x < 0.6$ so that the comparison is direct. No striking energy dependence in the antineutrino y -distributions is observed. This is more clear in Fig. 23, where the experimental results for $\langle y \rangle$ are shown as a function of energy. A constant value of B , $B \approx 0.8$, fits all antineutrino data reasonably. The B -values

*) The members of this group are: M. Holder, J. Knobloch, J. May, H.P. Paar, P. Palazzi, D. Schlatter, J. Steinberger, H. Suter, H. Wahl and E.G.H. Williams, (CERN), F. Eisele, C. Geweniger, K. Kleinknecht, G. Spahn and H.-J. Willutzki (Dortmund), W. Dorth, F. Dydak, V. Hepp, K. Tittel and J. Wotschack (Heidelberg), P. Bloch, B. Devaux, M. Grimm, J. Maillard, B. Peyaud, J. Rander, A. Savoy-Navarro and R. Turlay (CEN-Saclay), F.L. Navarria (Istituto di Fisica dell'Università, Bologna).

deduced from the y -distributions are shown in Fig. 24. The ratios of total cross-sections are given in Fig. 25 and can be seen to be independent of energy. In conclusion, these results a) do not reproduce any of the previously observed features of the "high- y anomaly", and b) show no energy variations inconsistent with scaling.

3.5 Other recent results concerning charged current reactions

In Fig. 26 the recent results²⁰⁾ on charged neutrino and antineutrino cross-sections are presented, as observed in BEBC filled with a neon-hydrogen mixture, and in the same beam as for the previous experiment. The ratio of the cross-sections seems to be rising with energy, chiefly because the neutrino cross-sections seem to be falling. However, the statistics are rather limited, and the results are not inconsistent with the uniform cross-section ratio of the CDHS experiment.

In Fig. 27, recent preliminary results of the CIT group on the dependence of $\langle y \rangle$ and the total cross-sections on energy are shown²¹⁾. These are also consistent with the CDHS results and do not confirm the high- y anomaly. The results on total cross-sections are summarized in Table 2.

Table 2

Neutrino and antineutrino total cross-sections and cross-section ratios

	GGM 1 < E < 5	BEBC 30 < E < 200	CIT 30 < E < 200	CDHS 30 < E < 200
$\frac{\sigma_{\nu}}{E} \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1} \text{ nucleon}^{-1}$	0.74 ± 0.05	0.59 ± 0.05	0.60 ± 0.06	
$\frac{\sigma_{\bar{\nu}}}{E} \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1} \text{ nucleon}^{-1}$	0.28 ± 0.03	0.27 ± 0.03	0.29 ± 0.03	
$\frac{\sigma_{\nu}}{\sigma_{\bar{\nu}}}$	0.38 ± 0.05	0.46 ± 0.07	0.48 ± 0.07	0.45 ± 0.05

No convincing deviation from scaling, except perhaps at the lowest energy, is observed.

4. NEUTRAL CURRENTS AND THE WEINBERG-SALAM MODEL

4.1 Preliminaries

Since their discovery in inclusive neutrino-nuclear reactions²⁾, neutral current effects have also been observed in neutrino-electron scattering²²⁻²⁴⁾ and in certain exclusive channels of neutrino-nuclear scattering^{25, 26)}. Although both

ν -e scattering and ν -nuclear exclusive scattering are potentially very informative about the structure of leptonic and hadronic neutral currents, we restrict ourselves here to new experimental results on the inclusive process.

We limit the discussion of the theoretical frame to vector and axial vector currents in the quark-parton model. However, the current is assumed to contain both left- and right-handed parts, in contrast with the charged current, which seems to be purely left-handed. Then we can write

$$\frac{d^2\sigma_\nu}{dx dy} = \frac{G^2 M E_\nu}{\pi} \left[A_L + A_R (1-y)^2 \right] \quad (1)$$

$$\frac{d^2\sigma_{\bar{\nu}}}{dx dy} = \frac{G^2 M E_{\bar{\nu}}}{\pi} \left[A_L (1-y)^2 + A_R \right],$$

where

$$A_L = A^- q(x) + A^+ \bar{q}(x); \quad A^- \leftrightarrow V - A$$

$$A_R = A^+ q(x) + A^- \bar{q}(x); \quad A^+ \leftrightarrow V + A.$$

The neutrino current is assumed to be of the form;

$$j_\nu = \bar{\nu} \gamma_\mu (1 - \gamma_5) \nu,$$

and the current of the four quarks of the G.I.M. model:

$$j_h = C_L^u \bar{u} \gamma_\mu (1 - \gamma_5) u + C_R^u \bar{u} \gamma_\mu (1 + \gamma_5) u$$

$$+ C_L^d \bar{d} \gamma_\mu (1 - \gamma_5) d + C_R^d \bar{d} \gamma_\mu (1 + \gamma_5) d$$

$$+ C_L^s \bar{s} \gamma_\mu (1 - \gamma_5) s + C_R^s \bar{s} \gamma_\mu (1 + \gamma_5) s$$

$$+ C_L^c \bar{c} \gamma_\mu (1 - \gamma_5) c + C_R^c \bar{c} \gamma_\mu (1 + \gamma_5) c.$$

In the Weinberg-Salam model, the eight vector and axial vector coupling constants are expressed in terms of a single parameter, the Weinberg angle θ_W :

$$C_L^u = C_L^c = 1 - \frac{4}{3} \sin^2 \theta_W; \quad C_R^u = C_R^c = -\frac{4}{3} \sin^2 \theta_W$$

$$C_L^d = C_L^s = -1 + \frac{2}{3} \sin^2 \theta_W; \quad C_R^d = C_R^s = +\frac{2}{3} \sin^2 \theta_W.$$

In this model, then,

$$A^- = \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W$$

and

$$A^+ = \frac{5}{9} \sin^4 \theta_W.$$

4.2 Results from the CDHS experiment

In the foregoing discussion of the high- y anomaly, the fundamental requirement in the event selection was the existence of a reconstructed track, the muon, and the possible existence of a hadron shower was ignored. In the discussion of neutral currents the process is reversed. We require a shower (energy deposit in 1.5 m of iron) of at least 12 GeV, and the possible existence of a muon track is ignored. However, for each shower, a so-called "event length" (EL) is established, which has as its aim the separation of the events into the two classes: neutral current (NC) and charged current (CC). In principle, this event length is the total length of the event, as evidenced by scintillator hits and drift chamber digitizings, from its beginning to its end (or to the end of the apparatus), measured in the thickness of iron. The beginning of the events accepted for the neutral current study has been restricted to the region $40 \text{ cm Fe} \leq z \leq 825 \text{ cm Fe}$. The event-length distributions are reproduced in Fig. 28. The large peak at small event lengths is due to neutral current events, the rest is due to charged current events. The step at $\text{EL} = 6 \text{ m Fe}$ is due to CC events with muons which leave the end of the apparatus. On the basis of Fig. 25, the data are divided into "neutral current" and "charged current" events by a cut at 2.1 m of iron.

A number of corrections have to be applied to the data, as can be seen in Table 3. The cosmic-ray background can be accurately determined by looking in a time slice outside of the 23 μsec beam spill. The background of CC events is determined by extrapolating the short muon events in the region $3 < \text{EL} < 5 \text{ m Fe}$ to the region $0 < \text{EL} < 2.1 \text{ m Fe}$ on the basis of the observed charged current y -distributions. The "wide-band" (WBB) background represents neutrino interactions from neutrinos with origin near the target, instead of the decay tunnel. It is evaluated on the basis of supplementary data with the hadron beam collimator closed. The K_{e3} background comes from events due to the reaction $\nu_e + \text{Fe} \rightarrow e + \dots$, since electrons are indistinguishable from hadrons in our apparatus. The ν_e flux is known, and this background can be calculated precisely on the basis of e - μ universality.

Table 3

Data reduction for the ratio of neutral current to charged current cross-sections for $E_H > 12$ GeV

	Neutrinos	Antineutrinos
NC candidates	10770 ± 104	3314 ± 58
Cosmic-ray background	-59 ± 7	-119 ± 10
WBB background	-286 ± 126	-646 ± 116
CC background	-1493 ± 64	-235 ± 49
NC with $L < 16$ and $L > L_{\text{cut}}$	$+150$	$+43$
K_{e3} correction	-1008	-154
NC signal	8074 ± 156	2203 ± 130
CC candidates	26509 ± 163	6483 ± 81
WBB background	-239 ± 117	-323 ± 83
CC extrapolation	$+1467 \pm 64$	$+253 \pm 42$
NC with $L > L_{\text{cut}}$	-134	-35
CC signal	27603 ± 211	6378 ± 123
NC/CC (error only statistical)	0.293 ± 0.006	0.346 ± 0.021
NC/CC (final result, systematic error included)	<u>0.295 ± 0.010</u>	<u>0.35 ± 0.03</u>

The comparison with the Weinberg-Salam model is made on the basis of the expressions

$$R_{\nu} = \frac{\sigma_{\text{NC}}}{\sigma_{\text{CC}}} \bigg|_{\nu} = \frac{1}{2} - \sin^2 \theta_W + \frac{20}{27} \sin^4 \theta_W ,$$

and

$$R_{\bar{\nu}} = \frac{\sigma_{\text{NC}}}{\sigma_{\text{CC}}} \bigg|_{\bar{\nu}} = \frac{1}{2} - \sin^2 \theta_W + \frac{20}{9} \sin^4 \theta_W .$$

In this comparison, a rather small correction is applied to the theoretical curve by means of a Monte Carlo calculation, to account for the neglect of events with $E_h < 12$ GeV.

In Fig. 29, these results, as well as previous results²⁷⁻²⁹), are compared with the predictions of the Weinberg-Salam model. From the CC y -distributions it is known that $\alpha = (1-B)/(1+B) = \int \bar{q}(x) dx / \int q(x) dx$ is quite close to 0.1. The Weinberg angle is most accurately determined by the neutrino measurement. The fact that the antineutrino result, with considerably smaller error than previous results, falls precisely on the "Weinberg nose", can be considered a check on the validity of the model.

Another step forward in our understanding of neutral currents becomes possible by making use of the hadron energy distributions at different detector radii. It will be remembered that different radii correspond to different hadron beam spectra, and the hadron energies reflect the y -distributions. The data are shown in Figs. 30 and 31.

The data can be analysed to yield information on the energy dependence of R_ν and $R_{\bar{\nu}}$. We find

$$\frac{R_\nu(E_\nu > 100 \text{ GeV})}{R_\nu(E_\nu < 100 \text{ GeV})} = 0.99 \pm 0.1$$

and

$$\frac{R_{\bar{\nu}}(E_{\bar{\nu}} > 100 \text{ GeV})}{R_{\bar{\nu}}(E_{\bar{\nu}} < 100 \text{ GeV})} = 1.03 \pm 0.30 .$$

This is in agreement with no energy variation. In order to study the y -distribution, we assume the form (1). Then

$$R_\nu(y) \propto \frac{1 + \alpha_{NC}(1-y)^2}{1 + \alpha_{CC}(1-y)^2}$$

and

$$R_{\bar{\nu}}(y) \propto \frac{(1-y)^2 + \alpha_{NC}}{(1-y)^2 + \alpha_{CC}}$$

where

$$\alpha_{CC} = \int q dx / \int \bar{q} dx$$

and

$$\alpha_{NC} = A_R/A_L .$$

If no further assumptions are made, the data of Fig. 31 yield the following result for α_{NC} , where, in the analysis, it has been assumed that $\alpha_{CC} = 0.1$:

$$\nu : \quad \alpha_{NC} = 0.21 \pm 0.14$$

$$\bar{\nu} : \quad \alpha_{NC} = 0.21 \pm 0.06 .$$

The solid lines in Fig. 31 represent this fit. The difference between α_{NC} and α_{CC} shows that the analysis of the relative hadron energy distribution of neutral and charged current events points to a non-zero V + A component of the neutral current. In the Weinberg-Salam model these values of α_{NC} yield values of $\sin^2 \theta_W$:

$$\text{from } \alpha_{NC}^V : \sin^2 \theta_W = 0.22 \pm 0.13$$

and

$$\text{from } \alpha_{NC}^{\bar{V}} : \sin^2 \theta_W = 0.25 \pm 0.05 .$$

These values, determined completely independently from the hadron energy distributions, agree well with the previously given value $\sin^2 \theta_W = 0.24 \pm 0.02$, determined solely from the ratios R_V and $R_{\bar{V}}$.

The data of Fig. 31 can also be used to study the question of the identity of the incident and outgoing neutrinos in neutral current reactions. If the two neutrinos are the same, then the ratio $(d\sigma_{\bar{V}}/dy)/(d\sigma_V/dy)|_{y=0}$ should be equal to 1³⁰⁾. If we assume that the charged current has this property (see also the experimental verification in Section 3), then for the neutral current we find, on the basis of the data of Fig. 31:

$$\left. \frac{d\sigma_{\bar{V}}}{dy} / \frac{d\sigma_V}{dy} \right|_{y=0} = 0.91 \pm 0.20 ,$$

in agreement with the expectation for identical neutrinos.

Finally, assuming neutrino identity, we can make a simultaneous fit to neutrino and antineutrino data, to find A_+ and A_- , the V + A and V - A compounds of the neutral current. The results, in Table 4, show that a small V + A term is required, although the uncertainty in this term is not negligible.

Table 4

Results of the neutral current study in terms of A_+ and A_- , the coefficients of V + A and V - A currents respectively

	Assumed	
	$\alpha_{CC} = 0.1$	$\alpha_{CC} = 0.15$
A_+	0.025 ± 0.006	0.031 ± 0.006
A_-	0.283 ± 0.007	0.280 ± 0.007

In the V,A frame for neutral currents (which includes, of course, the Weinberg-Salam model), the two numbers A_+ and A_- summarize the result of this neutral current experiment.

5. "WRONG SIGN" MUONS, CHARM CHANGING NEUTRAL CURRENTS,
AND THE SEA OF CHARMED PARTONS IN THE NUCLEON

If reactions with positive muons were observed among neutrino events, they could be due to the following processes:

- i) dimuon events, with short-range (invisible) negative muons;
- ii) neutral current reactions with subsequent $\pi^+ \rightarrow \mu^+$ or $K^+ \rightarrow \mu^+$ decay;
- iii) antineutrino charged current events, due to the "wide-band" background already discussed in the last section;
- iv) the neutral current, charm-changing reaction

This latter would be of great interest, since it is forbidden in the G.I.M. model.

We have observed 23 such events in a sample that contained 36,000 μ^- events. The number and the energy distribution of these events are consistent with wide-band background. No event is observed above $E_{\text{vis}} = E_{\mu^+} + E_h$ greater than 100 GeV. In this region we would expect a background of 3 events from processes (i) and (ii). To find an upper limit for the ratio of the cross-section of charm-changing neutral currents to that of charm-non-changing neutral currents, we use the fact that the sample contains 1100 NC events with $E_h \geq 100$ GeV, 0.15 for the muonic branching ratio, 0.5 for the muonic detection efficiency, to find

$$\frac{\sigma_{\text{charm-changing NC}}}{\sigma_{\text{normal NC}}} \leq \frac{2}{1100 \times 0.4 \times 0.15} = 0.04 \text{ (90\% confidence level) .}$$

6. MULTIMUONS

6.1 Preliminary

Opposite-sign dimuons produced by neutrinos were first observed in the HPWF experiment³¹⁾, and this was quickly followed by similar results from the CIT group³²⁾ and by the observation of μ^-e^+ events in the bubble chamber³³⁻³⁵⁾. The likely charmed origin of the bulk of these events was immediately clear. Less clear were the questions of the existence and nature of like-sign dimuons and of dimuons produced by antineutrinos. The last months have been marked by the following events:

- i) the observation of trimuons³⁶⁻³⁸⁾;
- ii) the claim³⁷⁾ that the observed trimuon events, as well as certain features of dimuon events, show that new processes, involving at least two new types of heavy leptons, are occurring;

- iii) substantially more extensive and better data on dimuon production by neutrinos and antineutrinos³⁹⁾;
- iv) more extensive bubble chamber data on $\mu^- e^+$ production by neutrinos³⁵⁾.

6.2 Opposite-sign dimuon results from the CDHS experiment³⁹⁾

A dimuon event, as reconstructed off line, is shown in Fig. 32. Observed event numbers for different event classes are shown in Table 5.

Table 5

Observed event numbers for single muon, dimuon and trimuon events

	ν	$\bar{\nu}$
Normal charged current	55,000	16,000
$\mu^- + \mu^+$	257	58
$\mu^- + \mu^-$	47	0
$\mu^+ + \mu^+$	0	9
$\mu^- + \mu^- + \mu^+$	1	$\frac{1}{2}$
$\mu^+ + \mu^+ + \mu$	1	0

It should be kept in mind, in evaluating these and subsequent data, that the minimum momentum required for the detection and momentum measurement of the muons is about 4.5 GeV/c, and that this represents a serious bias for most of the measured rates and distributions. Table 6 lists averages for some of the more interesting parameters.

In Figs. 33-36 some results for the opposite-sign dimuons are shown. Of particular interest are the x-distributions, which are very different from those of normal CC events, and the correlations in transverse momentum of the second muon^{*)}, which show that the second muon, independent of its energy, has a close correlation with the hadron shower direction. The average transverse momentum of the second muon with respect to this direction is 0.7 GeV. All of the results are in good agreement with the expectations of the G.I.M. model, where the muon is

*) The first muon is the one whose electric charge is the same as that of normal charged current reactions.

Table 6
Average values of certain parameters for single muon and dimuon reactions

Reaction	$\nu \rightarrow \mu^- + X$	$\bar{\nu} \rightarrow \mu^+ + X$	$\nu \rightarrow \mu^- + \mu^+ + X$	$\bar{\nu} \rightarrow \mu^- + \mu^+ + X$	$\nu \rightarrow \mu^- + \mu^- + X$	$\bar{\nu} \rightarrow \mu^+ + \mu^+ + X$
E_{total} (GeV)	93 ± 1	70 ± 1	108 ± 3	85 ± 6	133 ± 7	97 ± 16
E_{μ_1} (GeV)	53 ± 1	50 ± 1	45 ± 2	37 ± 4	52 ± 5	53 ± 11
E_{μ_2} (GeV)	-	-	13.7 ± 1	12.4 ± 1	7.3 ± 0.6	5.7 ± 0.5
X	0.29 ± 0.01	0.27 ± 0.01	0.24 ± 0.01	0.15 ± 0.02	0.26 ± 0.04	0.33 ± 0.13
y	0.44 ± 0.01	0.30 ± 0.01	0.58 ± 0.02	0.57 ± 0.03	0.59 ± 0.03	0.48 ± 0.06

the decay of a charmed particle, most often the D^+ , in the decay mode $D \rightarrow K + \mu^+ + \nu$. We recall that the principal reactions in the G.I.M. model and their relative rates are the following:

$$\begin{array}{l} \nu + d \rightarrow c + \mu^- + \dots \propto \sin^2 \theta_c \times \text{BR} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^+ + \dots \\ \nu + s \rightarrow c + \mu^- + \dots \propto \zeta_s \cos^2 \theta_c \times \text{BR} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^+ + \dots \end{array}$$

and

$$\bar{\nu} + \bar{s} \rightarrow \bar{c} + \mu^+ \quad \propto \zeta_s \cos^2 \theta_c \times \text{BR} ,$$

where ζ_s is the momentum carried by the strange sea quarks relative to the valence d quarks: $\zeta_s = \int x s(x) dx / \int x d(x) dx$.

In the case of antineutrinos, the model predicts that the dimuon production is almost entirely associated with the strange sea. The corresponding x-distribution of Fig. 34 is then a measure of the x-distribution of this sea. It is strikingly different from the x-distributions normally found in experiments on neutrino, electron, and muon inelastic scattering, which are presumably dominated by valence quarks. In the case of neutrinos, the contribution from valence quarks seems to be comparable to that from the sea, so that the small factors $\sin^2 \theta_c$ and ζ_s are comparable.

The excitation functions are given in Fig. 37, where also the calculated muon detection efficiencies, assuming the charm production model of Sehgal and Zerwas⁴⁰⁾, are shown. From a comparison of these $\bar{\nu}$ and ν production ratios corrected for the muon detection efficiencies, and the relative $\bar{\nu}/\nu$ charged cross-sections (0.43 ± 0.02), the strange sea component in the nucleon can be directly found:

$$\zeta_s = 0.035 \pm 0.01 \text{ .}$$

From a comparison of the dimuon-CC ratio and the G.I.M. model production cross-sections, the charm to muon branching ratio is ~ 0.15 . Since a similar value is found in electron-positron colliding beam experiments, the argument can be turned around to furnish a quantitative check of the G.I.M. model.

Another check of the G.I.M. model is provided by the comparison of the average observed energy compared to the average neutrino energy, as deduced from the beam kinematics. This ratio is observed to be 0.92 ± 0.04 , indicating that $8 \pm 4\%$ of the total energy is lost to the missing neutrino in the charm decay. This can be seen also by comparing Fig. 38 with Fig. 4, where the observed energy is plotted against detector radius for dimuon and single muon events, respectively.

Table 6
Average values of certain parameters for single muon and dimuon reactions

Reaction	$\nu \rightarrow \mu^- + X$	$\bar{\nu} \rightarrow \mu^+ + X$	$\nu \rightarrow \mu^- + \mu^+ + X$	$\bar{\nu} \rightarrow \mu^- + \mu^+ + X$	$\nu \rightarrow \mu^- + \mu^- + X$	$\bar{\nu} \rightarrow \mu^+ + \mu^+ + X$
E_{total} (GeV)	93 ± 1	70 ± 1	108 ± 3	85 ± 6	133 ± 7	97 ± 16
E_{μ_1} (GeV)	53 ± 1	50 ± 1	45 ± 2	37 ± 4	52 ± 5	53 ± 11
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y	0.44 ± 0.01	0.30 ± 0.01	0.58 ± 0.02	0.57 ± 0.03	0.59 ± 0.03	0.48 ± 0.06

the decay of a charmed particle, most often the D^+ , in the decay mode $D \rightarrow K + \mu^+ + \nu$. We recall that the principal reactions in the G.I.M. model and their relative rates are the following:

$$\begin{array}{l} \nu + d \rightarrow c + \mu^- + \dots \propto \sin^2 \theta_c \times \text{BR} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^+ + \dots \end{array}$$

$$\begin{array}{l} \nu + s \rightarrow c + \mu^- + \dots \propto \zeta_s \cos^2 \theta_c \times \text{BR} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^+ + \dots \end{array}$$

and

$$\begin{array}{l} \bar{\nu} + \bar{s} \rightarrow \bar{c} + \mu^+ \\ \quad \quad \quad \downarrow \\ \quad \quad \quad \mu^- \end{array} \propto \zeta_s \cos^2 \theta_c \times \text{BR} ,$$

where ζ_s is the momentum carried by the strange sea quarks relative to the valence d quarks: $\zeta_s = \int x s(x) dx / \int x d(x) dx$.

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$$\zeta_s = 0.035 \pm 0.01 .$$

From a comparison of the dimuon-CC ratio and the G.I.M. model production cross-sections, the charm to muon branching ratio is ~ 0.15 . Since a similar value is found in electron-positron colliding beam experiments, the argument can be turned around to furnish a quantitative check of the G.I.M. model.

Another check of the G.I.M. model is provided by the comparison of the average observed energy compared to the average neutrino energy, as deduced from the beam kinematics. This ratio is observed to be 0.92 ± 0.04 , indicating that $8 \pm 4\%$ of the total energy is lost to the missing neutrino in the charm decay. This can be seen also by comparing Fig. 38 with Fig. 4, where the observed energy is plotted against detector radius for dimuon and single muon events, respectively.

6.3 Results from the FNAL 15' neon-filled bubble chamber³⁵⁾

In a wide-band neutrino exposure, 81 events of the type $\nu + \text{Ne} \rightarrow \mu^- + e^+ + \dots$ were identified. The main advantage of these data over those in the counter experiment are that a) even small-energy positrons can be detected, and b) the neutral strange particles can be identified.

To the extent that comparison is possible, the bubble chamber and counter results are in agreement. In Fig. 39 the e^+ energy spectrum, and the x- and y-distributions are reproduced. The observed strange-particle rate, assuming the unobserved charged particles are equal in number to the neutrals, corresponds to about one strange particle per event. All results are consistent with the expectations of the G.I.M. model.

6.4 Results from like-sign dimuons from CDHS⁴¹⁾

The raw rates are about seven times less than for opposite-sign dimuons, and the problem of background from charged current interaction with a pion or kaon decay is severe. According to our calculations $\sim (65 \pm 20)\%$ of the events are background of this sort. The distributions in the momentum of the lower energy muon and in y are shown for data and background calculations in Figs. 40 and 41. The calculated background distributions are quite consistent with the data. The remaining like-sign dimuon rate is $\approx (0.05 \pm 0.03)$ of the opposite-sign rate. We cannot be sure that it is not zero. The data are consistent with a charmed pair origin for these events, corresponding to a fraction of the order of $(0.5 - 1.0)\%$ of the charged current events. The data do not seem to be consistent with a cascading heavy lepton model of trimuon production, which predicts like-sign dimuons with both muons energetic, at rates which would have been very visible⁴²⁾.

7. STRUCTURE FUNCTIONS FOR THE QUARK-ANTIQUARK "SEA"⁴³⁾

In Section 6.2 we drew attention to the fact that charm production by anti-neutrinos is expected to be purely from antiquarks in the "sea". The corresponding x-distribution (Fig. 34b) is therefore a direct measure of the x-distribution of sea quarks. It was seen to be very different from the normally observed x-distributions, which are due to valence quarks.

Another direct glimpse of the "sea" can be had by looking at normal charged current events produced by antineutrinos at large values of y. Since the quark contribution, in this case, falls as $(1-y)^2$, the sea dominates at large y. In the interval $0.8 < y < 1$ the valence quarks can be expected to contribute only $\approx 15\%$ of all events, and the sea quarks $\approx 85\%$. In the neutrino case the situation is reversed, and the sea can be expected to contribute only a few per cent in this

y-region. In Fig. 42 the two x-distributions are shown, for this y-interval and for all charged current events with $E_\nu > 30$ GeV. The difference is striking. The x-distribution for neutrinos at high y does not differ greatly from that at other y-values. However, the x-distribution for antineutrinos is remarkably shifted to low x, and indistinguishable from the x-distribution of the antineutrino dimuon events, Fig. 34b. When the small contributions of valence quarks are subtracted, the distributions of Fig. 42 and Fig. 34b are well fitted with the distribution of the form $(1-x)^8$. It should be noted that, in the G.I.M. model, the "dimuon sea" is dominated by strange quarks and the "single-muon sea" by up quarks. Nevertheless the two distributions are very similar.

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Figure captions

- Fig. 1 : Over-all layout of neutrino area at SPS.
- Fig. 2 : Narrow-band beam optics at SPS.
- Fig. 3 : Geometry underlying neutrino energy determination.
- Fig. 4 : Observed energy for charged current events versus the impact radius in the detector, illustrating the beam kinematics. The bands show the kinematical regions for pion and kaon neutrinos.
- Fig. 5 : Neutrino event rates as a function of the measured energy ($E_{\mu} + E_n$) in a particular radial annulus, as observed in the CDHS experiment.
- Fig. 6 : Wide-band and narrow-band neutrino and antineutrino spectra as seen by the CDHS detector.
- Fig. 7 : CDHS detector.
- Fig. 8 : Test calorimeter results on pulse-height distributions for hadrons and electrons at several energies.
- Fig. 9a : Test calorimeter results on the resolution for hadrons and electrons as a function of energy.
- Fig. 9b : The average pulse-height as a function of the hadron (electron) energy.
- Fig. 10 : Lines of constant final hadron mass W and lines of constant muon angle in the x-y plot.
- Fig. 11 : Compilation of x-distributions observed in inelastic neutrino scattering⁹⁾.
- Fig. 12 : y-distributions observed in Gargamelle¹⁰⁾.
- Fig. 13 : Total cross-section as a function of neutrino energy. Compilation⁹⁾ of Gargamelle¹¹⁾, ANL¹²⁾ and FNAL¹³⁾ results.
- Fig. 14 : First HPWF results¹⁴⁾ on anomalous behaviour in the antineutrino cross-section at high energy and high y . The y -distribution for antineutrinos with $x < 0.1$ is nearly flat, much higher at large y than would be expected from scaling lower energy results.

- Fig. 15a : HPWF results¹⁵⁾ on neutrino and antineutrino y -distributions at lower energies, $E_\nu < 30$ GeV. These are reasonably consistent with lower energy Gargamelle results.
- Fig. 15b : HPWF results¹⁵⁾ on neutrino and antineutrino y -distributions for $E_\nu > 70$ GeV. The increase in the antineutrino cross-sections at high y is a very striking departure from scaling.
- Fig. 16 : HPWF result¹⁵⁾ for the behaviour of the average y , $\langle y \rangle$, as a function of the energy. The rise in $\langle y \rangle$ for neutrinos is a reflection of the acceptance. The rise for antineutrinos is interpreted as a change in the B parameter from ≈ 0.9 at lower energies to ≈ 0.4 at higher energies, a dramatic violation of scaling.
- Fig. 17 : Compilation¹⁷⁾ of B_ν versus E_ν of HPWF, CIT and 15' FNAL bubble chamber results.
- Fig. 18 : HPWF result¹⁸⁾ on the energy variation of the total cross-section ratio $\sigma_\nu/\sigma_{\bar{\nu}}$.
- Fig. 19 : Comparison of acceptances of HPWF, CIT and CDHS apparatuses at two energies.
- Fig. 20 : Distribution in total (neutrino) energy for 36,000 neutrino and 12,000 antineutrino events.
- Fig. 21 : Normalized y -distributions for neutrino and antineutrino data, with and without a cut $x < 0.1$. The distributions are normalized to the same ν and $\bar{\nu}$ fluxes subject to a relative scale error of $\pm 10\%$.
- Fig. 22 : CDHS y -distributions in the x -interval $x < 0.6$, for neutrinos and antineutrinos in two energy regions: $30 < E_\nu < 40$ GeV and $100 < E_\nu < 150$ GeV. The rapid fall at large y , relatively more important at low neutrino energy, is due to the limited muon acceptance of the apparatus.
- Fig. 23 : The average values of y as a function of neutrino energy, for neutrino and antineutrino data. The curves marked $B = 0.8$ are calculated for the acceptance of the CDHS experiment. The HPWF data are taken from Ref. 15.
- Fig. 24 : The B -values as a function of antineutrino energy, from various experiments^{10, 15-17, 19)}.

- Fig. 25 : The ratio of neutrino and antineutrino total cross-sections as a function of neutrino energy. The data marked HPWF1 and HPWF2 are taken from Ref. 16.
- Fig. 26 : Neutrino and antineutrino total cross-section results on the BEBC Collaboration²⁰⁾.
- Fig. 27 : Preliminary results for $\langle y \rangle$ and total cross-sections, for neutrinos and antineutrinos, from the CIT Collaboration²¹⁾.
- Fig. 28 : "Event length" distributions for neutrinos and antineutrinos. The peak at short length is due to neutral current events, the rest due to charged current events.
- Fig. 29 : The results for the ratios R_ν and $R_{\bar{\nu}}$ compared with the Weinberg-Salam model. Also shown are the results of the Gargamelle Collaboration²⁷⁾, the CIT group²⁸⁾ and the HPWF Collaboration²⁹⁾.
- Fig. 30 : Hadron energy distributions for different radial bins for CC and NC and for a) neutrino and b) antineutrino events.
- Fig. 31 : Ratio of neutral to charged current events as a function of hadron energy for different radial bins, for a) neutrinos and b) antineutrinos.
- Fig. 32 : A dimuon event, computer reconstructed, in the CDHS experiment³⁹⁾.
- Fig. 33 : Correlations between the momenta of the two muons³⁹⁾. The shaded areas in the energy distributions of the second muon is the calculated $\pi \rightarrow \mu$ and $K \rightarrow \mu$ decay background. The solid curve is calculated on the basis of a charm production model.
- Fig. 34 : x- and y-distributions for neutrino and antineutrino events. The solid curves are calculated on the basis of a charm production model. The dotted curves are the flat and $(1-y)^2$ distributions which dominate the normal charged current reactions.
- Fig. 35 : Scatter plot in azimuthal angle of μ_2 versus E_{μ_2} , for neutrinos and antineutrinos. The predictions of a charm model are shown in the projections.
- Fig. 36 : Scatter plot in the transverse momentum of the second muon a) with respect to the leading muon (p_T), and b) with respect to the hadron shower direction (p_{Tsh}), versus the energy of the first muon.

- Fig. 37 : The dimuon/single muon event ratios as a function of the total observed energy. The acceptance, as predicted in the charm model is also shown.
- Fig. 38 : Correlation of energy of opposite-sign dimuon events and detector radius. Comparison with Fig. 4 permits an estimate of the average amount of energy lost to outgoing neutrinos.
- Fig. 39 : Some properties of the μ^-e^+ events observed in the FNAL 15' neon-filled chamber³⁵⁾. a) Positron spectrum. b) x-distribution. c) y-distribution.
- Fig. 40 : Correlations in the more energetic (μ_1) and less energetic (μ_2) muons, for the CDHS like-sign dimuon events. The calculated $\pi \rightarrow \mu$ and $K \rightarrow \mu$ background is also shown.
- Fig. 41 : x- and y-distributions for the CDHS like-sign dimuon events. The solid curve in the y-distribution is the form of the expected $\pi \rightarrow \mu$ and $K \rightarrow \mu$ background.
- Fig. 42 : x-distributions at large y, $0.8 < y < 1.0$, for neutrino and anti-neutrino CC events, with $E_\nu > 30$ GeV.

Fig. 1

Fig. 2

$$\theta_{\text{decay}} \approx r / (L + L_d / 2)$$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

$\frac{dN}{dx}$ NEUTRINOS

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

Fig. 27

Fig. 28

NEUTRINO EVENTS

Fig. 30a

ANTINEUTRINO EVENTS

Fig. 30b

$$R_V = NC / CC$$

Fig. 31a

$$R_{\nabla} = NC / CC$$

Fig. 31b

CERN DORTMUND HEIDELBERG SACLAY NEUTRINO EXPERIMENT WAI

NEP
 RUN/EVENT 2441 25219
 BITCLA 58
 BITS 00065 40007
 EHAD 67.9 24.9
 HADVERT 520 227 4356
 EHAD 3.6 2.7
 HADVERT 223 -133 8446

TRACK NR.	X	1	+	2
ZVERT		4356.0		4484.0
XVERT		497.2		500.3
	+-	15.0		9.0
YVERT		218.8		206.5
	+-	11.4		8.5
PX		-1.5		.6
	+-	.2		.1
PY		-1.9		.6
	+-	.2		.1
P*SIGN		-23.1		23.6
	+-	1.5		1.7
CHI2/ND		17./19		11./19
MUFLXI		0000034		0000034

Fig. 32

Fig. 33

Fig. 34

Fig. 34

Fig. 35

Fig. 36

Fig. 37

Fig. 38

Fig. 39

Fig. 40

Fig. 41

Fig. 42