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SEARCH FOR ANOMALIES IN HIGH ENERGY CHARGED CURRENT NEUTRINO INTERACTIONS*

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INTRODUCTION

The high energy inelastic neutrino processes involving a single final-state muon, i.e. $\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) +$ hadrons, are of importance to the study of elementary particles in two broad areas. In the first place, the approximate scaling behavior predicted and observed in the analogous electromagnetic processes[1] has led to a simple quark picture for nucleon structure that appears to at least qualitatively explain the observed behavior of these neutrino collisions at moderate energies. Second, and of even more importance, large-scale deviations from this picture at higher energies[2] may indicate a new physical regime. We should differentiate small modifications to the quark picture, such as logarithmic deviations to scaling, or even the damping effects at large momentum transfers (Q^2), such as those expected from propagator effects, from the energy threshold effects expected for production of new hadronic or leptonic states. In view of the exciting new discoveries[3,4] at SPEAR and BNL, and the avid expectations written on the faces of the theorists around us, we experimentalists cannot help but be infected by this spirit and pay very close attention to the last of these possibilities.

In Table I, I have outlined the "conventional picture" for neutrino collisions on heavy targets, beginning with the differential cross-sections expected in the general case for a V-A interaction. Following this, the usual assumptions applied to these expressions are written in the order of their established reliability at low energies. Some recent evidence in this regard should be noted. The Gargamelle group[5] has recently published their analysis for the Adler sum rule, theoretically valid at infinite energy ($E \gg Q^2/2M$), which predicts that the differential cross-section difference between neutrino and anti-neutrino (neglecting $\Delta S = 1$ interactions) should vanish for targets of isopin zero. Figure 1 shows that this difference is consistent with zero as $Q^2/E \rightarrow 0$, corroborating the charge symmetry principle observed in weak decays. The scaling and Callen-Gross relations are verified only to about 10-20% in the regions of validity, and are known[6,7] to be seriously broken at low Q^2.

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TABLE I

$$\frac{d\sigma^{\nu}}{dxdy} = \frac{G^2ME}{\pi}\left[q_{\nu}(\nu,Q^2) + \bar{q}_{\bar{\nu}}(\nu,Q^2)\ (1-y)^2 + K_{\nu}(\nu,Q^2)\ (1-y)\right]\frac{\Lambda^4}{(Q^2+\Lambda^2)^2}$$

$$\frac{d\sigma^{\bar{\nu}}}{dxdy} = \frac{GME}{\pi}\left[\bar{q}_{\bar{\nu}}(\bar{\nu},Q^2) + q_{\bar{\nu}}(\nu,Q^2)\ (1-y)^2 + K_{\bar{\nu}}(\nu,Q^2)\ (1-y)\right]\frac{\Lambda^4}{(Q^2+\Lambda^2)^2}$$

Other notation: $K = F_2 - 2xF_1$; $\bar{q} = \dfrac{2xF_1 + xF_3}{2}$; $q = \dfrac{2xF_1 - xF_3}{2}$

Assumption		Evidence (Low Energy)
Charge symmetry	$\left\{\begin{array}{l} q_{\nu} = q_{\bar{\nu}} \\ \bar{q}_{\nu} = \bar{q}_{\bar{\nu}} \\ K_{\nu} = K_{\bar{\nu}} \end{array}\right\}$	Weak decays GGM ν expts – Adler sum rule
High mass propagator	$Q^2 << \Lambda^2$	
Scaling	$q(\nu,Q^2) = q(x)$ $Q^2 > 1\ \mathrm{GeV}^2$ $W^2 > 4\ \mathrm{GeV}^2$	SLAC eN good to ~10 – 20% For $Q^2 < 1\ \mathrm{GeV}^2$ large deviations independent of W
Callen-Gross Relation	$K = 0$ $(F_2 = 2xF_1)$	SLAC eN known violations 0(10%) May be wrong by ~20% at small x.
"Small anti-quark"	$\bar{q}(x) << q(x)$ $x > 0.1$	Must be wrong at small x GGM: $\alpha = \dfrac{\int\bar{q}(x)dx}{\int F_2(x)dx} \simeq .06$ all x $\dfrac{\int\bar{q}(x)dx}{\int q(x)dx} \equiv \dfrac{\bar{Q}}{Q} = 0.29$ for $x < 0.1$

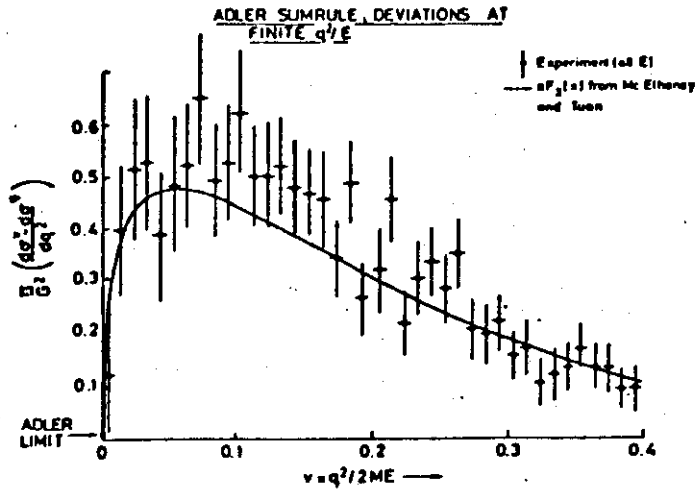


Fig. 1

Variation with $q^2/2ME$ of the difference between neutrino and antineutrino cross sections showing that convergence to the Adler limit occurs only at very small values.

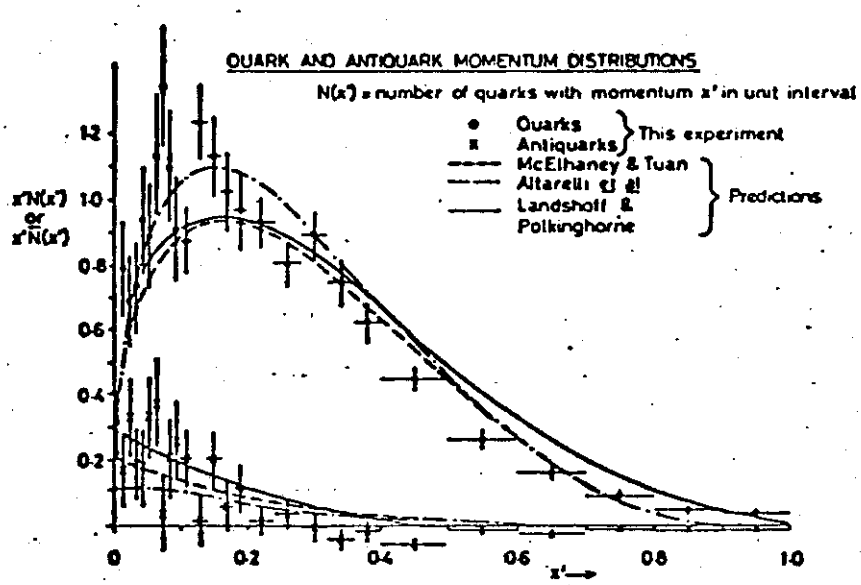


Fig. 2

The quantities $x'\bar{N}(x') = \frac{1}{2}[\bar{F}_2(x') - x'\bar{F}_3(x')]$ and $x'N(x') = \frac{1}{2}[\bar{F}_2(x') + x'\bar{F}_3(x')]$ deduced from the distributions in figs. 4 and 5. At asymptotically high energies, these would represent the distributions of total momentum carried by the antiquarks and quarks respectively. The areas under the two distributions represent the fractional nucleon momentum carried by all antiquark or quark constituents. The curves represent the asymptotic predictions of Landshoff and Polkinghorne [13], McElhaney and Tuan [14] and Altarelli et al. [17], in all cases based on fits of quark momentum distributions to electron scattering data.

The "small anti-quark" statement, written last, simplifies the mathematics, but must be applied with caution. It is expected[8] theoretically to be badly broken at small x; i.e. $q(o) = \bar{q}(o)$. This is consistent with the experimental determination[5] of these quantities obtained by the Gargamelle experiment, shown in figure 2. These distribution functions are obtained from a direct comparison of neutrino and anti-neutrino cross-sections in the energy region $E \leqslant 15$ GeV.

Since we are very interested in the question of new particle production, the low energy behavior is of some relevance when making comparisons to determine whether some energy threshold has been passed. To roughly 20% accuracy, therefore, we expect that high energy neutrino collisions will be determined by

$$\frac{d\sigma^{\nu}}{dxdy} = \frac{G^2ME}{\pi} \left[q(x) + \bar{q}(x)\ (1 - y)^2\right]$$

$$\frac{d\sigma^{\bar{\nu}}}{dxdy} = \frac{G^2ME}{\pi} \left[\bar{q}(x) + q(x)\ (1 - y)^2\right]$$

where $q(x)$, $\bar{q}(x)$ are more or less as shown in figure 2. Because the Gargamelle data are at low energy, some differences might be expected at low x (low Q^2), where the SLAC-MIT data indicate the poorest agreement with scaling.[6] But large-scale deviations from these relations, especially when they occur beyond some well-defined energy threshold, might be the signal we seek for the emergence of new states of matter.

HIGH ENERGY CROSS-SECTIONS

The integrated forms of equations (1) and (2) are

$$\sigma^{\nu} = \frac{G^2ME}{\pi}\left[Q + \frac{1}{3}\bar{Q}\right], \quad \sigma^{\bar{\nu}} = \frac{G^2ME}{\pi}\left[\bar{Q} + \frac{1}{3}Q\right]$$

where $Q = \int q(x)\ dx$ and $\bar{Q} = \int \bar{q}(x)\ dx$.

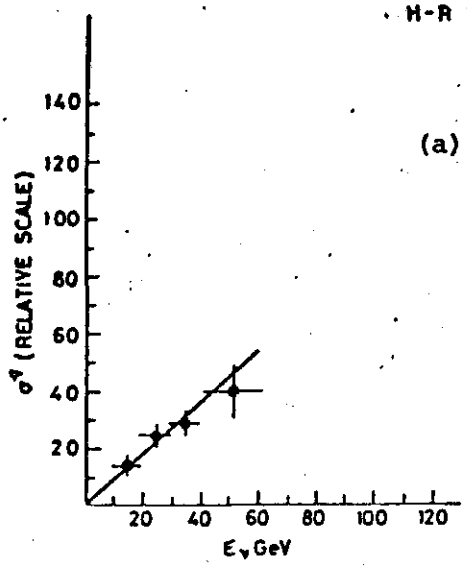
These relations illustrate the expected linear rise with neutrino energy, and an expected total cross-section ratio of <u>roughly</u> 1/3 (for $\bar{Q} < Q$). Up to about 100 GeV, no serious discrepancy from the expected behavior has been seen.

Figure 3 shows the high-energy cross-sections measured[9] by the Harvard-Pennsylvania-Wisconsin-Fermilab collaboration (HPWF). These are obtained using the Hagedorn-Ranft calculated neutrino flux distributions, normalizing to the low energy cross-sections for quasi-elastic scattering. Their measured slopes up to 80 GeV, with accuracies of about 25%, agree well with the normalized cross-sections measured at CERN ($E \leqslant 15$ GeV).

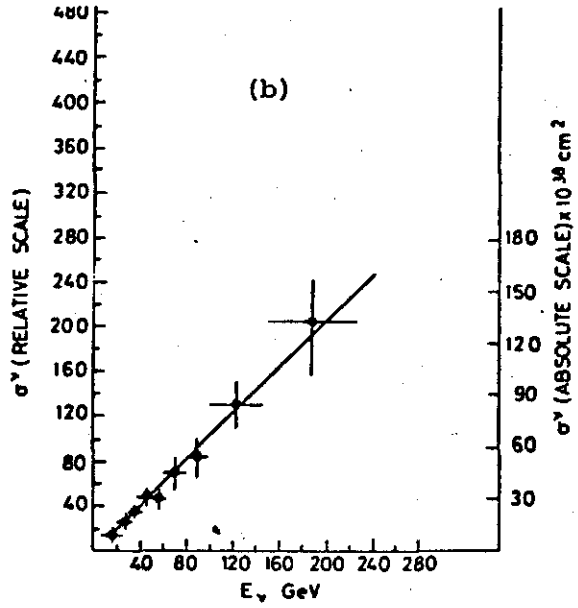
The Caltech-FNAL experiment has thus far measured normalized cross-sections at two neutrino energies, utilizing the direct flux-measuring techniques[10] that can be applied in the narrow band beam.

HPWF

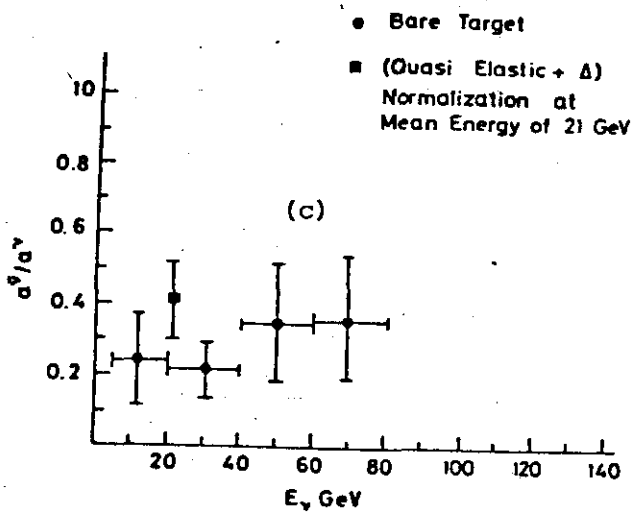
Fig. 3



Total cross-section as a function of anti-neutrino energy.



Total cross-section as a function of neutrino energy.



Cross section ratio as a function of energy. Bare target measurements are from Reference 1.

The best slope value for the sum of σ_ν and $\sigma_{\bar{\nu}}$ up to 100 GeV, shown in figure 4, are within one-standard deviation (about 10%) of the low-energy measurements. Figure 4 also shows[11] that the measurement of the effective mean-square charge of the constitutents, obtained by comparison of electron-scattering and neutrino scattering, continues to indicate fractional charge for nucleon constituents when high energy neutrinos are used as probes.

HIGH ENERGY DIFFERENTIAL DISTRIBUTIONS

One year ago, the status of the high energy distributions was mixed. The Caltech-Fermilab group had concluded[11,12] from a sample of 1500 neutrino events at 50 and 150 GeV that no serious anomalies were visible in the shapes of the differential distributions. In particular, the Q^2 behavior predicted by the SLAC-measured $F_2(x)$ and a flat y-dependence for dominant q(x) gave good agreement with the data. A mass limit of 10 GeV/c^2 on the mass of an intermediate vector boson propagator was quoted on this basis.

The HPWF group, on the other hand, saw[2,9] what they felt was a serious anomaly in the y-distributions of $\bar{\nu}$, especially beyond 30 GeV anti-neutrino energy. Since then, they have determined[13] that their anomaly exists only in a restricted range of x, $x<0.1$. This is illustrated[14] in figure 5, which shows the y-distributions for ν and $\bar{\nu}$ in two bands of x. For $x>0.1$, they have normalized so that the ν and $\bar{\nu}$ intercept the same point at $y = 0$, as required by charge symmetry. Using the same normalization for $x<0.1$, they find that the $\bar{\nu}$ data lie uniformly lower than the ν data by a factor of about 0.36.

Although this effect has been dubbed a "high-y anomaly", I believe that the level for $\frac{dN}{dy}$ at large y is close to what is expected from low energies. Figure 2 shows that the Gargamelle small-x values for q(x) and $\bar{q}(x)$ are

$$q(x) \approx 0.85, \quad \bar{q}(x) \approx 0.25 \text{ for } x < 0.1.$$

Equations (1) and (2) then predict for $x < 0.1$

$$\frac{d\sigma^{\nu}}{dy} = \frac{G^2 ME}{\pi} \left[0.85 + 0.25\ (1-y)^2\right]$$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \frac{G^2 ME}{\pi} \left[0.25 + 0.85\ (1-y)^2\right]$$

For large y, we expect

$$\lim_{y \to 1} \frac{d\sigma^{\bar{\nu}}}{dy} \Big/ \frac{d\sigma^{\nu}}{dy} = \frac{0.25}{0.85} = 0.29$$

consistent with the ratio 0.36 observed by HPWF.

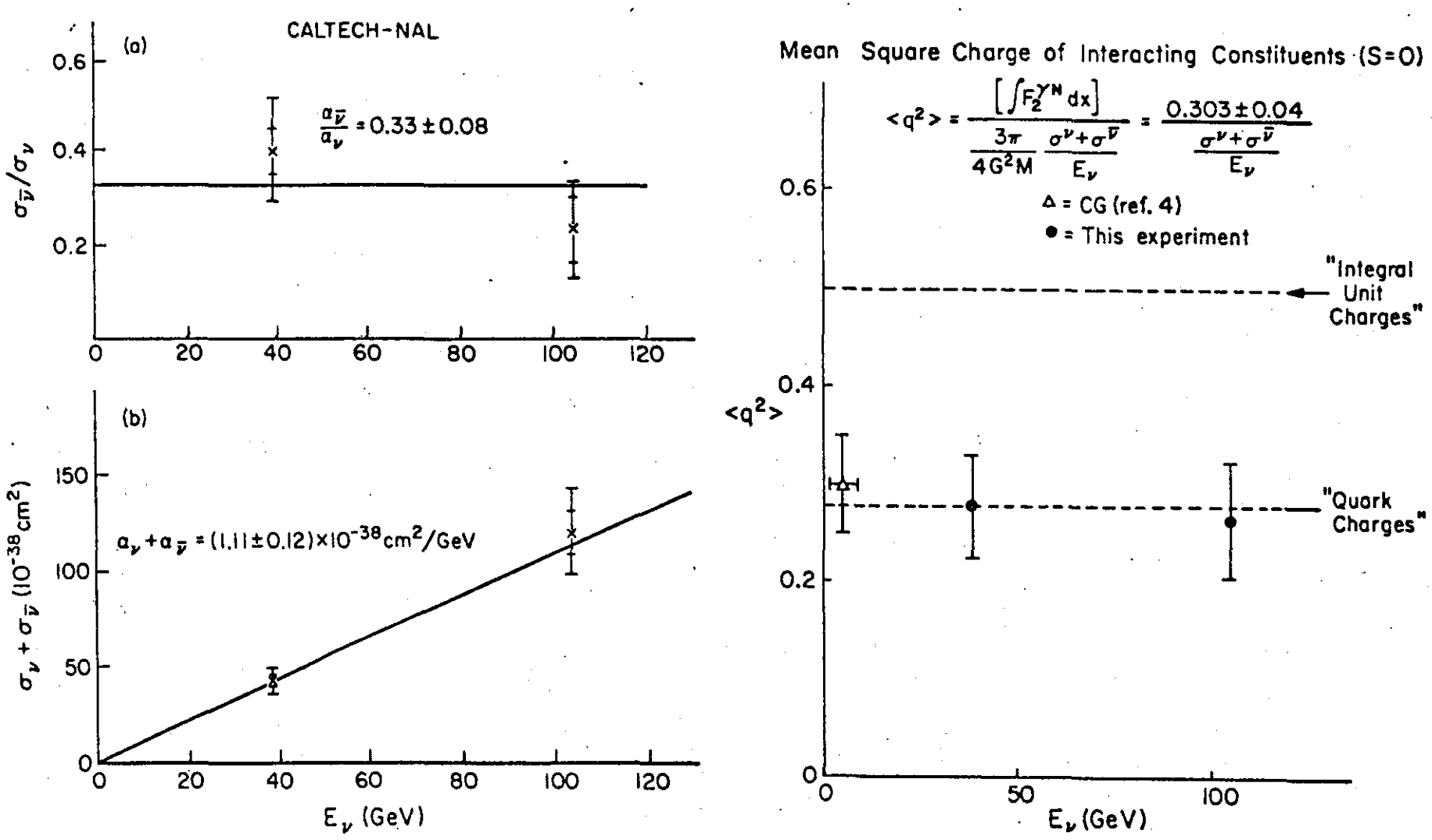

CALTECH-NAL
(a)
$\frac{a_{\bar{\nu}}}{a_\nu} = 0.33 \pm 0.08$
$\sigma_{\bar{\nu}}/\sigma_\nu$
0.6
0.4
0.2
0
20
40
60
80
100
120
(b)
$a_\nu + a_{\bar{\nu}} = (1.11 \pm 0.12) \times 10^{-38} cm^2/GeV$
$\sigma_\nu + \sigma_{\bar{\nu}}$ ($10^{-38} cm^2$)
150
100
50
0
E_ν (GeV)
Mean Square Charge of Interacting Constituents (S=0)
$\langle q^2 \rangle = \frac{\left[\int F_2^{\gamma N} dx\right]}{\frac{3\pi}{4G^2M} \frac{\sigma^\nu + \sigma^{\bar{\nu}}}{E_\nu}} = \frac{0.303 \pm 0.04}{\frac{\sigma^\nu + \sigma^{\bar{\nu}}}{E_\nu}}$
Δ = CG (ref. 4)
● = This experiment
"Integral Unit Charges"
"Quark Charges"
$\langle q^2 \rangle$
0.6
0.4
0.2
0
50
100
E_ν (GeV)

Fig. 4

HPWF

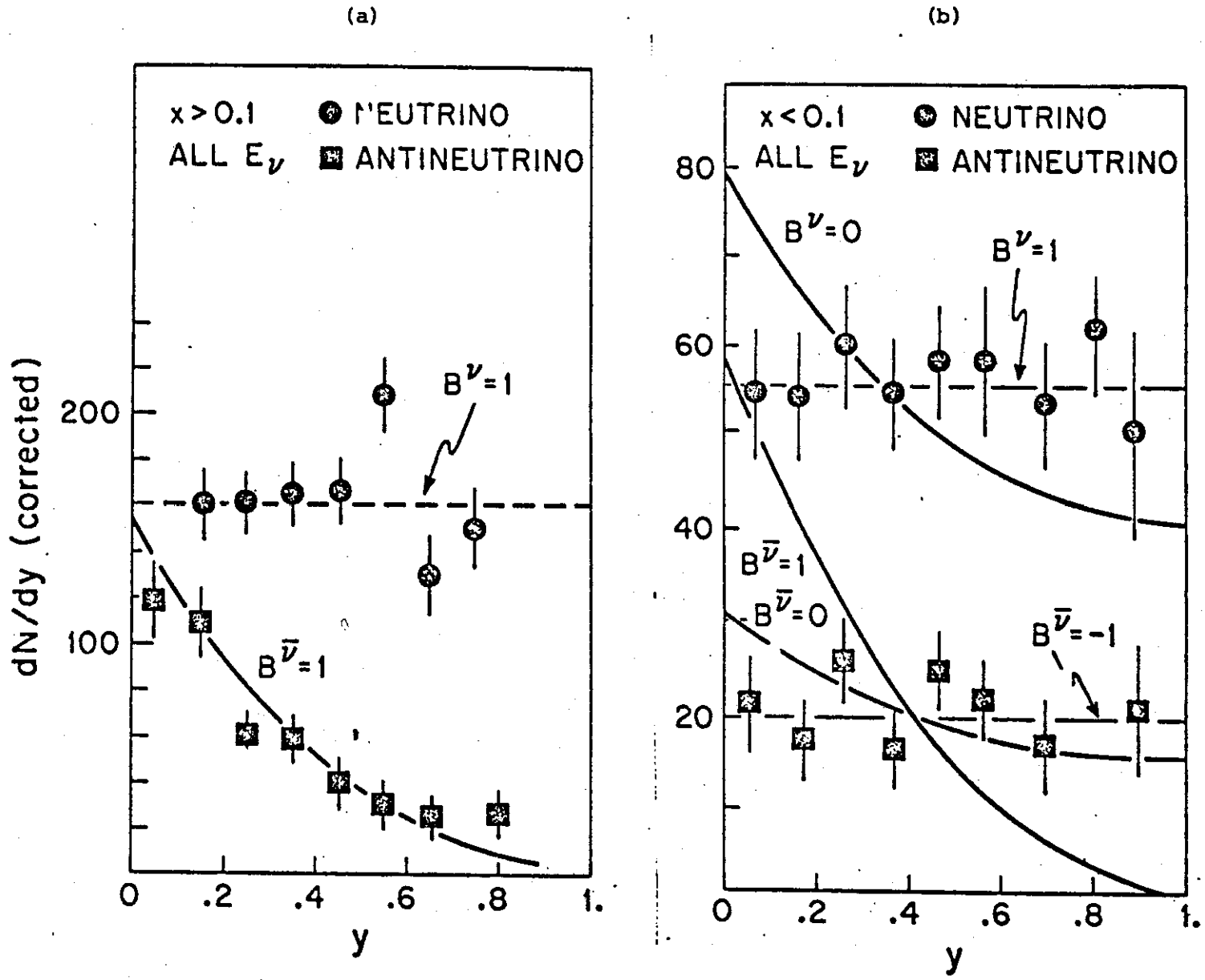

(a)
(b)
x > 0.1
ALL E_ν
NEUTRINO
ANTINEUTRINO
$B^\nu = 1$
$B^{\bar\nu} = 1$
dN/dy (corrected)
200
100
0
.2
.4
.6
.8
1.
y
x < 0.1
ALL E_ν
NEUTRINO
ANTINEUTRINO
$B^\nu = 0$
$B^\nu = 1$
$B^{\bar\nu} = 1$
$B^{\bar\nu} = 0$
$B^{\bar\nu} = -1$
80
60
40
20
0
.2
.4
.6
.8
1.
y

Fig. 5

The behavior at small y and small x is not explained so simply, however. From Table I, for fixed energy neutrinos,

$$\frac{dN^{\nu}}{dy} = \frac{dN^{\bar{\nu}}}{dy} \qquad y \to 0.$$

This relation depends on V-A and charge symmetry and is independent of scaling, Callen-Gross, or any of the other assumptions shown in Table I. The data of figure 5 appear to violate this relation by a factor of 3, whereas the relation, broken only by neutron-proton target excess, and strangeness-changing currents, should be valid to about 5-10%.

The fact that this anomaly occurs at small y makes it unlikely to be from the production of new high mass hadronic states by anti-neutrinos. The typical anti-neutrino energy in the HPWF data is about 30 GeV. The average energy transfer to the hadron system for $y < 0.1$ and $E_{\nu} \simeq 30$ GeV is $\nu = 3$ GeV, corresponding to $W \approx 2.2$ GeV, a relatively low mass value. Also, the data are characterized by an absence of expected events at small y, rather than an excess.

This region of small y and small x, it should be noted, is characterized by typical values of energy and four-momentum transfer, respectively, of $\nu \leqslant 3$ GeV and $Q^2 \leqslant 6$ GeV^2. This is just the region of Q^2, ν where Gargamelle finds[5] consistency with the requirements of charge symmetry, again making it unlikely to be from production of new hadrons.

Two possibilities remain for the observed effect. (1) Because the initiating neutrinos have much higher energy than those at CERN, anomalies could be the result of new interactions at the lepton vertex. (2) The data have been taken with a wide-band beam, which has a different spectrum for neutrinos and anti-neutrinos. In addition, cuts in Q^2 and W have been applied to remove "quasi-elastic events". The effect of such energy-dependent cuts on neutrino and anti-neutrino data of differing energies must be clearly understood before we can rule out this possibility.

The Caltech-Fermilab group, in the process of carrying out their neutral current program, has recently acquired and analyzed a sample of anti-neutrino data which bear on this question. This data is almost entirely from pion neutrinos of mean energy $\langle E_{\nu} \rangle = 50$ GeV. Figure 6b shows the experimentally-observed energy spectrum of reconstructed anti-neutrino events.

In order to test for consistency with lower energy inelastic scattering, the parameterization shown in figure 7 has been adopted. The assumed form for $F_2(x) = q(x) + \bar{q}(x)$ assumes the Callen-Gross relation, and is the empirical expression found to describe electron-deuteron inelastic scattering.[15] The form for $\bar{q}(x) = \frac{1}{2} e^{-bx} F_2(x)$ satisfies the requirements $\bar{q}(o) = q(o)$, and $\bar{q}(x) < F_2(x)$ for all x. Quantitative conclusions regarding the total integrated fraction ($\alpha = \int \bar{q}(x)\, dx / \int F_2 dx$) are somewhat dependent on this parameterization, it should be noted, although statements made in restricted x regions (e.g. $x < 0.1$) do not depend on such details.

Although the overall efficiency for obtaining charged-current

CITF DATA – DISTRIBUTIONS IN TOTAL OBSERVED ENERGY NARROW BAND BEAM CHARGED-CURRENTS

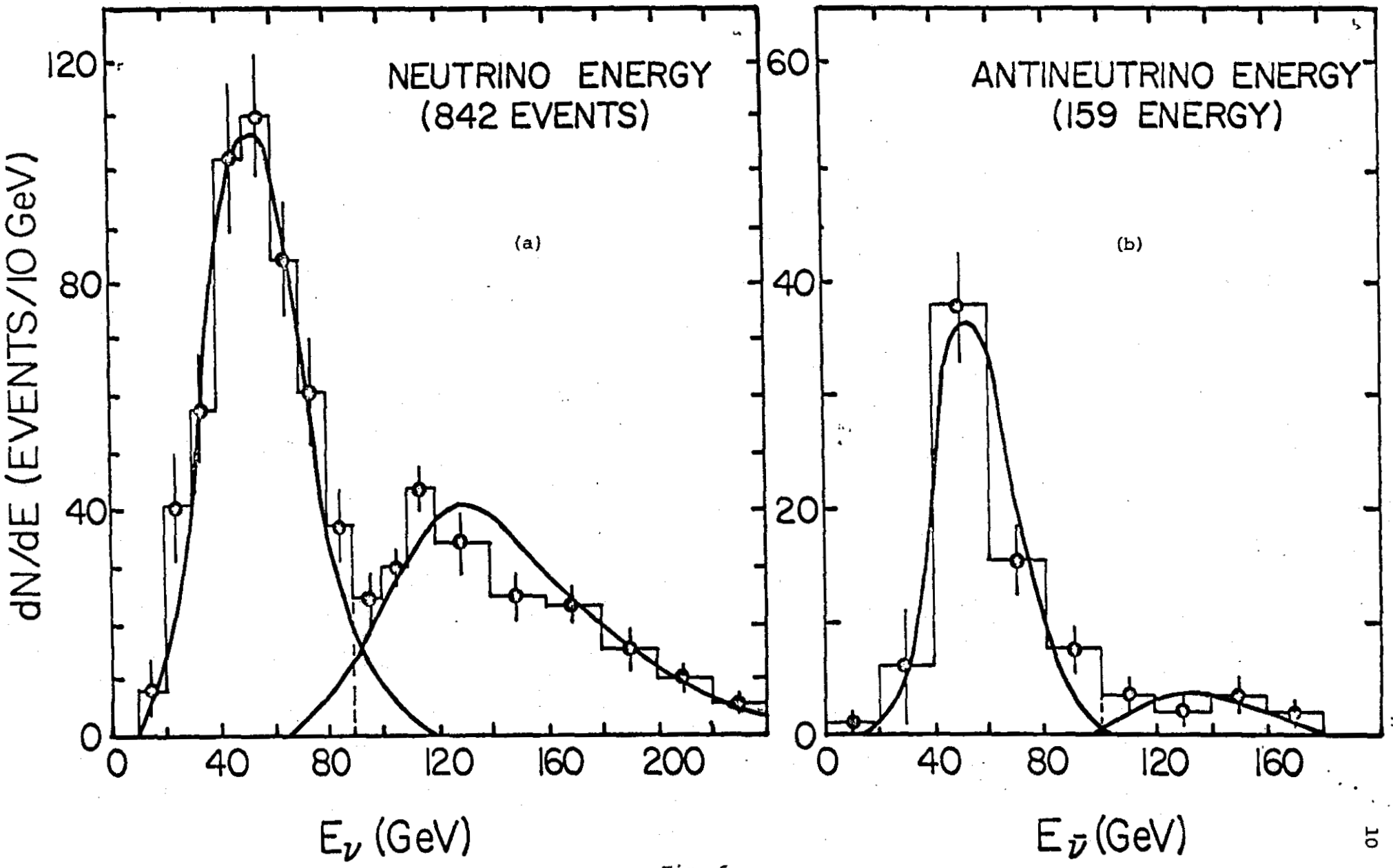


Fig. 6

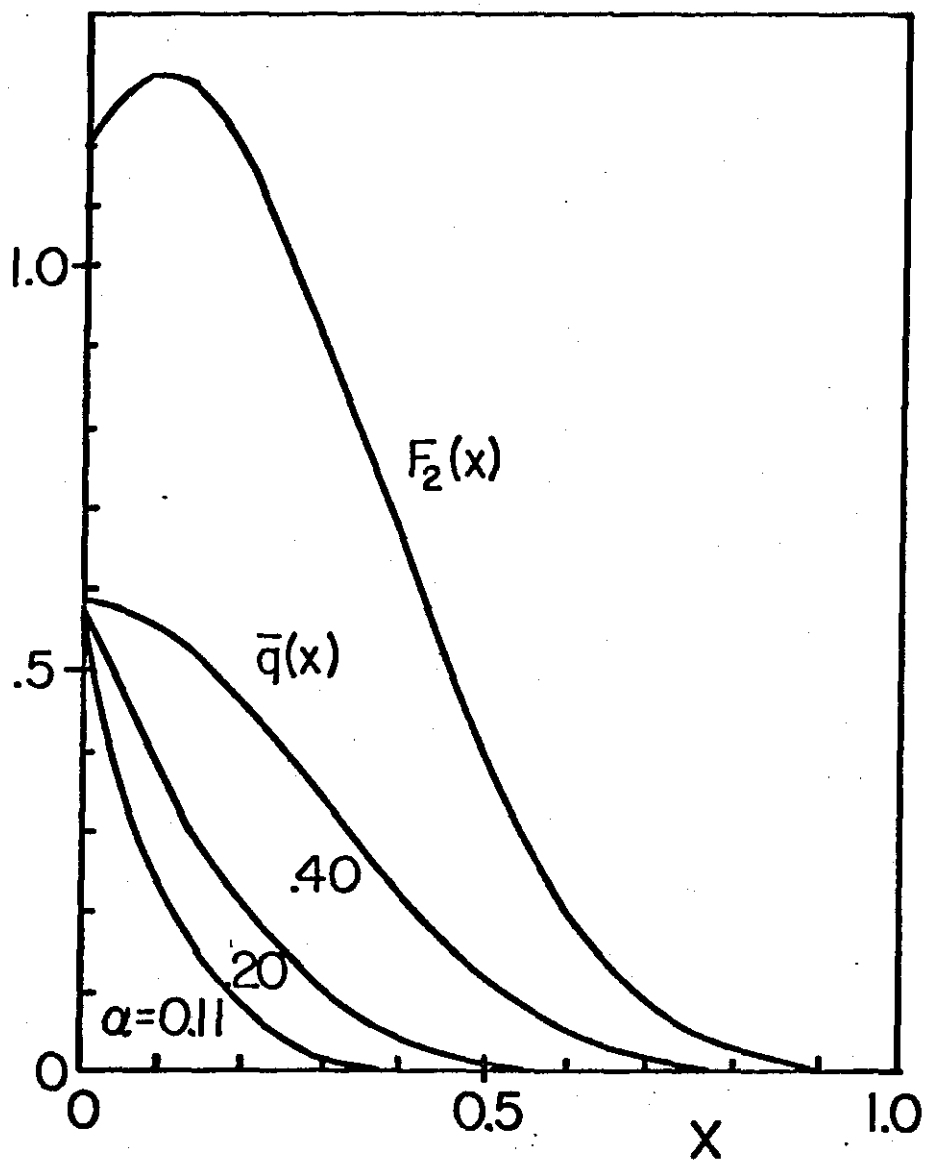


Fig. 7

<u>Assumed parametrization of x-dependence</u>

$$F_2(x) = q(x)+\bar{q}(x) = \sum_{i=3}^{7} c_i(1-x)^i$$

$$\bar{q}(x) = \frac{1}{2}e^{-bx}\,F_2(x)$$

$c_3 = 3.276$
$c_4 = -7.168$
$c_5 = 31.22$
$c_6 = -44.56$
$c_7 = 18.384$

<u>$\bar{Q}$ component</u>

$$\alpha \equiv \frac{\int \bar{q}(x)dx}{\int F_2(x)dx} \qquad 0 \le \alpha \le 0.5$$

events in this experiment was high (~85%), a substantial fraction do not have the muon energy directly measured because of solid angle restrictions for the magnetic spectrometer. Fortunately, the narrow band beam with an energy spectrum peaking at 50 GeV, and a width of about 25%, provides a direct relationship between measured hadron energy (ν) and $y = \nu/E_\nu$.

Figure 8a shows the observed y-distribution for the 85 events with measured final-state muon and with $x > 0.1$. These data, consistent with $\alpha = 0.11$ as shown, are actually rather insensitive to variations in α. The data (Fig. 8b) with $x < 0.1$ are more sensitive. The curves for $\alpha = 0$ and $\alpha = 0.11$ are normalized to the data of figure 8a. As figure 8b shows, the data at small x prefer some $\bar{q}$ component to provide signal at large y as seen in the data. The distribution in hadron energy, figure 8c, for events with the muon unmeasured, also prefer some finite $\bar{q}$-component. The χ^2 for the simultaneous fit to these distributions, shown in figure 8d, is quite consistent with $\alpha = 0.11$ for the relative integrated anti-quark component, and is not in good agreement with $\alpha = 0$ or $\alpha = 0.5$.

The distribution in invariant mass (figure 9a) reflects this requirement for some events with large y. The data contains events with rather large invariant mass, which again requires some finite $\bar{q}$ component (e.g. curve with $\alpha = 0.11$). The experimental distribution in y, for $x < 0.1$, is shown again in figure 9b. Here the data have been corrected for efficiency. The curve with $\alpha = 0.11$, shown for comparison, is again quite consistent with the data. The statistical errors are such that a flat distribution with normalization as a free parameter could not be ruled out.

Because of the charge symmetry question at small y raised earlier in connection with the HPWF data, it is of some interest to treat the CIT data in a similar manner. Figure 9c shows the $x < 0.1$ neutrino and anti-neutrino data normalized such that the data with $x > 0.1$ have equal $\frac{dN}{dy}$ at $y = 0$. This figure should then be compared with figure 5b. In this case, the anti-neutrino data are entirely consistent with the same intercept at $y = 0$ as the neutrino data. A flat distribution lying a factor 0.36 below the neutrino data would lie below all of the data points, as shown in the figure. This data does not, therefore, show the same low y behavior discussed in connection with the HPWF data. It should be noted that this data was taken in the narrow-band beam and has not been cut in any kinematic variables.

Recent theoretical interest in the possibility of right-handed hadronic currents[11,17] (with "charm"), together with the observation of new hadronic states at SPEAR, prompts a further investigation of this 50 GeV $\bar{\nu}$ data. Such right-handed currents would be especially visible in anti-neutrino collisions, since the y-distribution would go from a dominant $(1-y)^2$ behavior below threshold to an approximate $[1 + (1-y)^2]$ dependence well above threshold. At $E_\nu = 50$ GeV, the energy is well above threshold for the production of 3 GeV hadrons with the kinematic region for production lying at $y(1-x) \geqslant .08$. In the absence of a detailed threshold dependence, fits have been attempted to the y-distribution with the expression

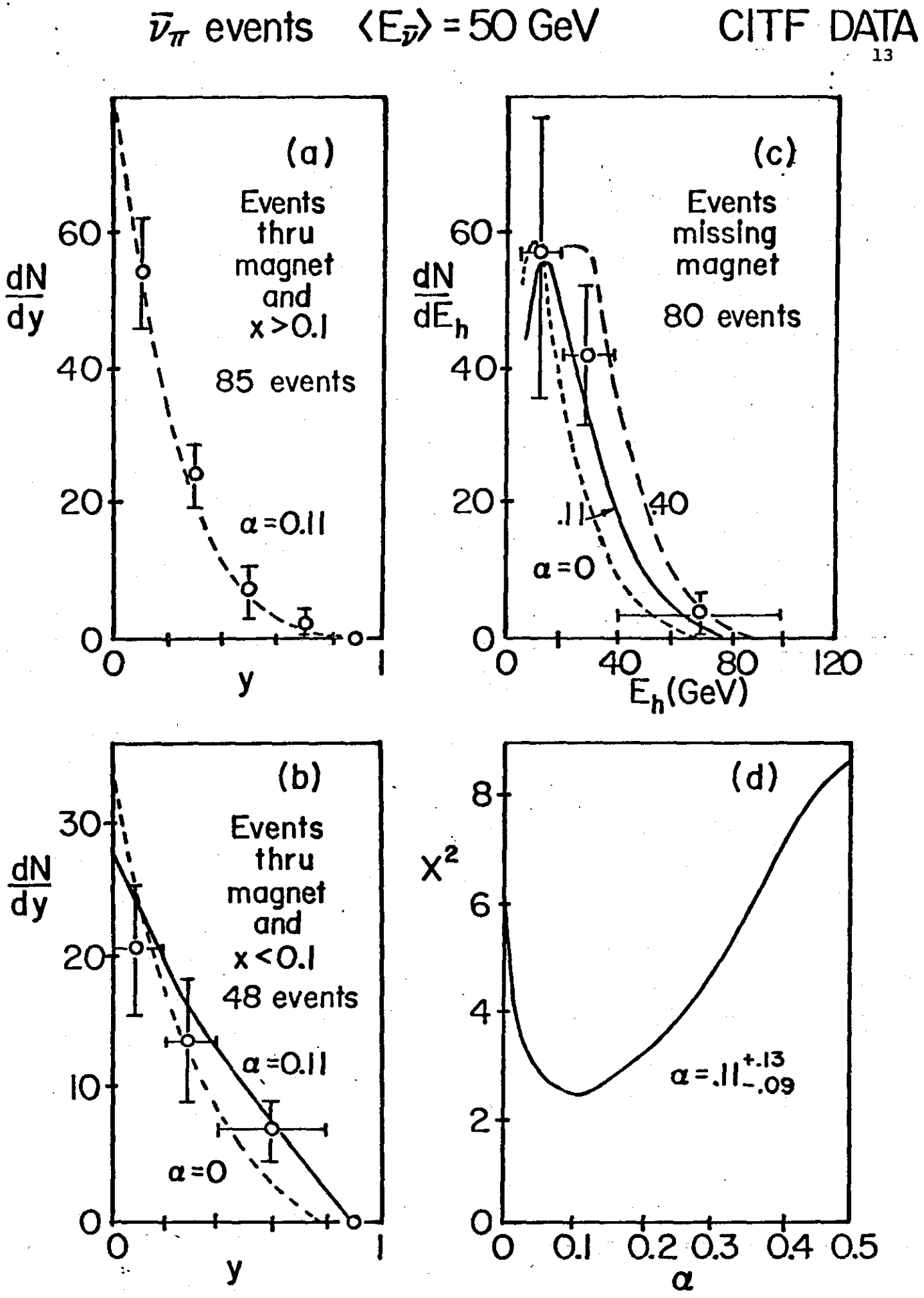

$\bar{\nu}_\pi$ events $\langle E_{\bar{\nu}} \rangle = 50$ GeV
CITF DATA
(a)
Events thru magnet and x>0.1
85 events
α=0.11
dN/dy
y
(b)
Events thru magnet and x<0.1
48 events
α=0.11
α=0
dN/dy
y
(c)
Events missing magnet
80 events
.11
40
α=0
dN/dE_h
E_h(GeV)
(d)
X²
α = .11 +.13 −.09
α

Fig. 8

CITF DATA

$\bar{\nu}_\pi$ events $\langle E_{\bar{\nu}} \rangle = 50$ GeV

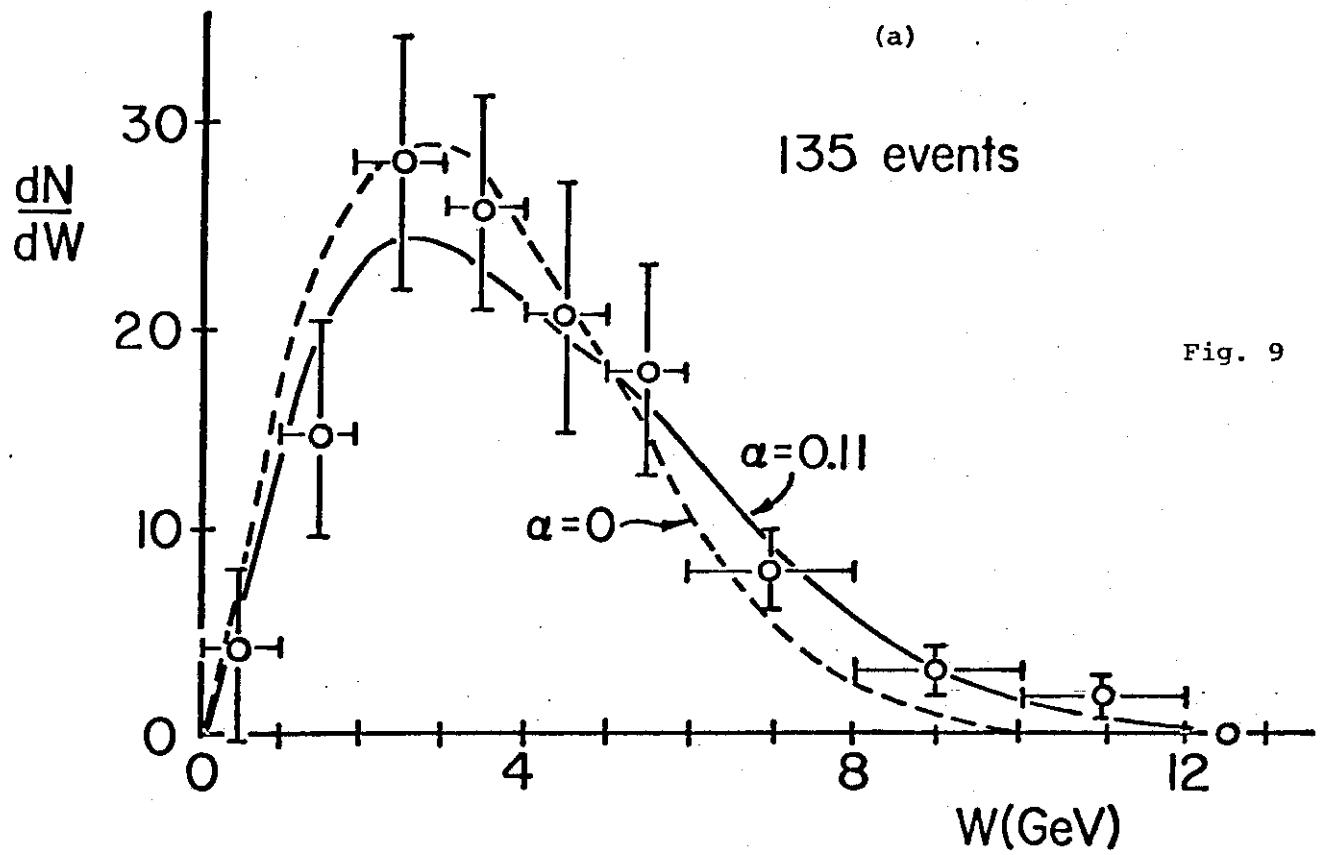
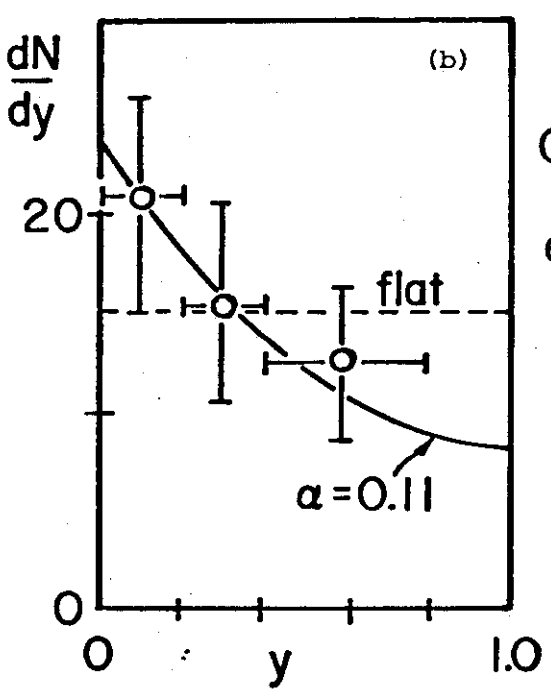
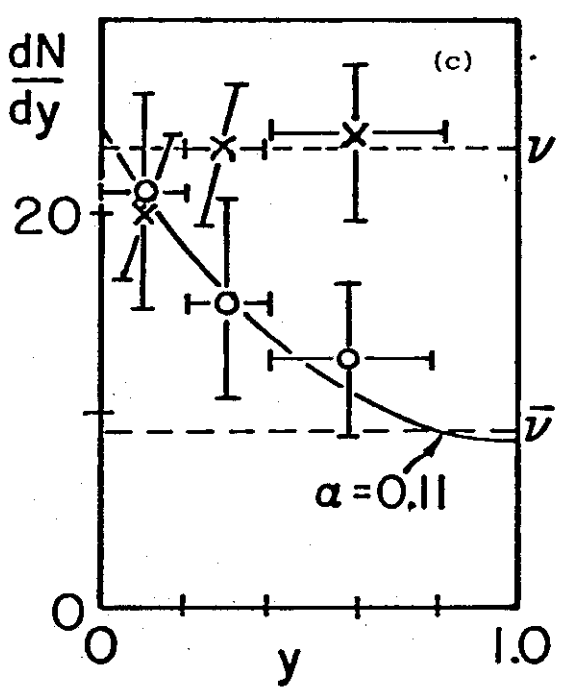


Fig. 9



x < 0.1
Corrected
for
efficiency



CITF Data

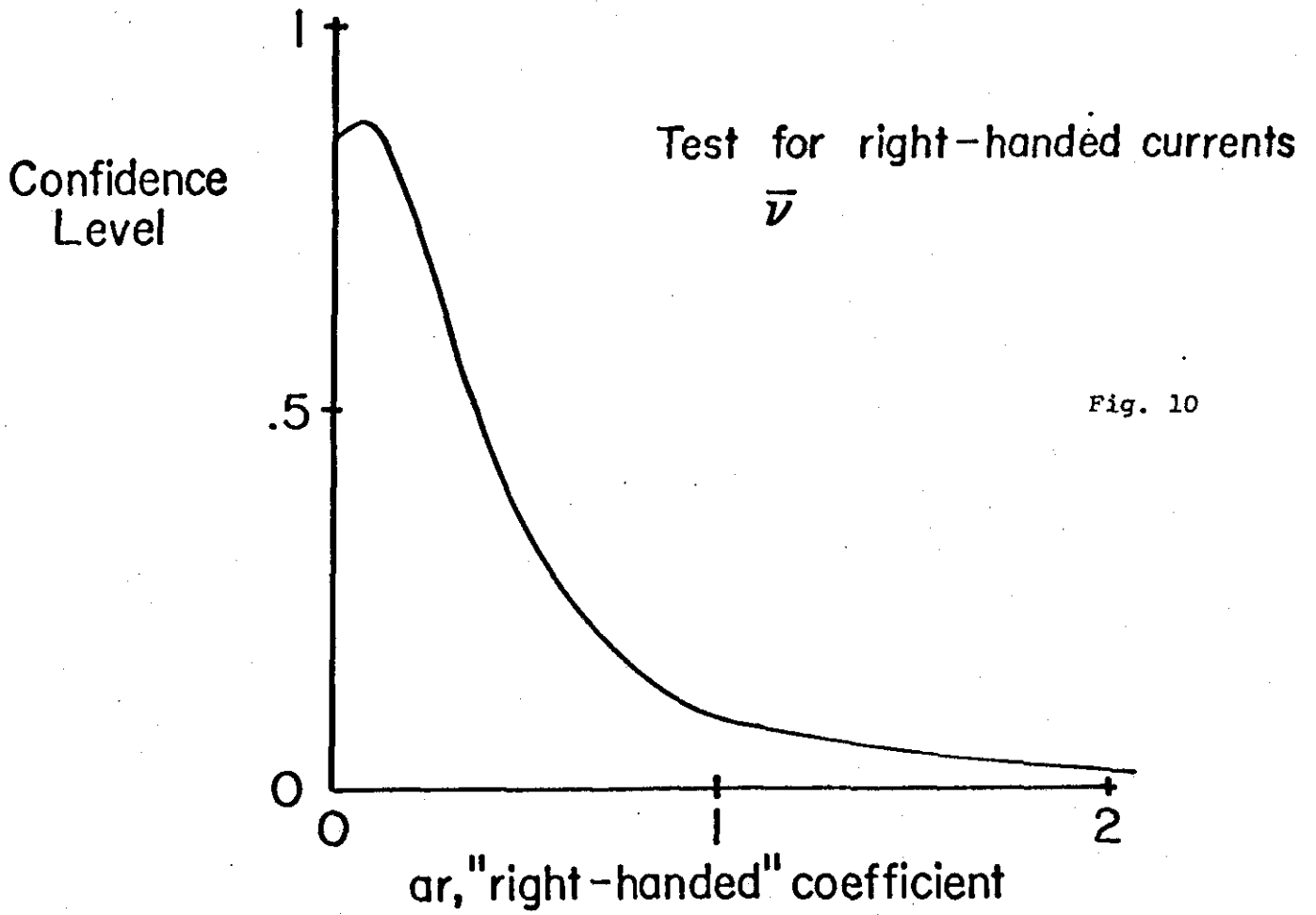


Fig. 10

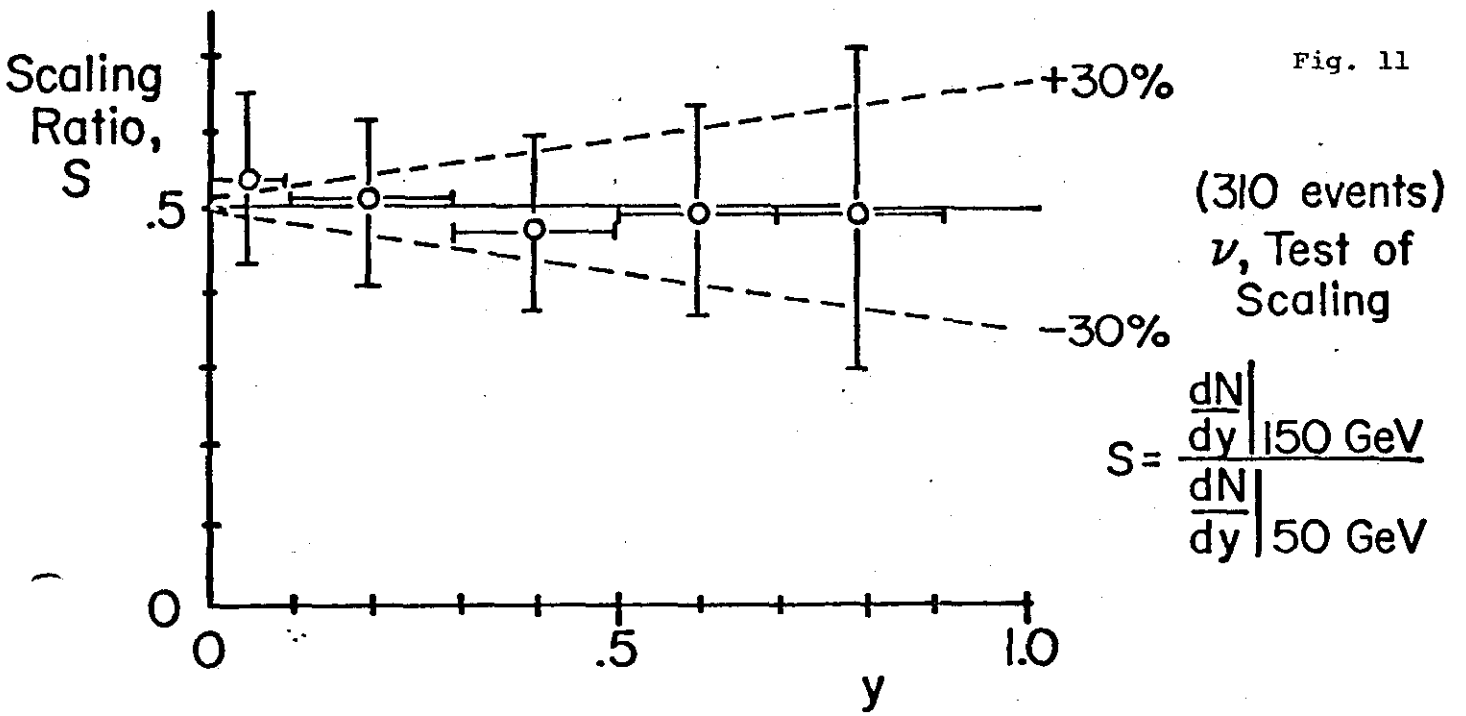


Fig. 11

$$\frac{dN}{dy} = C \left\{ [q(x)\ (1-y)^2 + \bar{q}(x)] + a_r\,[q(x) + \bar{q}(x)\ (1-y)^2] \right\}$$

where a_r is the effective coupling of a new right-handed current, and $q(x)$, $\bar{q}(x)$ are the quark and anti-quark distribution functions discussed previously for 11% anti-quark component. Figure 10, showing the confidence level vs a_r for the $\bar{\nu}$ data, rules out $a_r = 1$ at about the 10% probability level. It is very unlikely that such right-handed currents are appearing copiously in anti-neutrino collisions at 50 GeV.

The neutrino data taken in the same run with observed energy distribution as shown in figure 6a, shows complete consistency with the best parameterization found for the anti-neutrino case. Here the data consists of comparable signal from 50 GeV and 150 GeV neutrino collisions. Because of the large signal observed in di-muon production by neutrinos at 150 GeV, it is of some interest to investigate whether there is any indication for large-scale changes between the two energies in the ordinary charged-current events.

The Caltech apparatus measures muon energy for only a subset of events with relatively small muon angle, θ. At fixed inelasticity, y, the event x-value is given to leading order by

$$x = \frac{E\theta^2}{2M}\ \frac{1-y}{y}$$

Different target fiducial cuts were made on the 50 and 150 GeV events, such that $E\theta^2$ = constant. This provides the same efficiency at fixed y, for the two neutrino energies. A Monte-Carlo check of this procedure shows that it provides a direct check on scaling to better than 5%. The ratio of 150 GeV/50 GeV data vs y is shown in figure 11. The data is completely consistent between the two energies, although the statistics are such that 30% deviations cannot be ruled out. This procedure will be applied to data taken in the coming months, which will contain many more energies, and will have direct, independently measured normalizations.

Using the x-parameterization already discussed, the Q^2 dependence of the neutrino data can be predicted. Figure 12 shows the 50 GeV and 150 GeV Q^2 distributions directly measured in the experiment. No deviations from expected behavior shown as smooth curves, are seen. The high energy data are such that propagator masses less than 14 GeV/c^2 can now be excluded.

SUMMARY

We anticipate that we might soon be seeing neutrino production of new hadronic and/or leptonic states; indeed, the recent results in dimuon production by neutrinos may be the first hints of such effects. However, in my opinion, the charged-current data standing alone, thus far has not demonstrated that such anomalies exist.

(1) No evidence for the opening of new channels in visible in total production rates up to about 100 GeV.

CITF DATA – Q^2 DISTRIBUTIONS

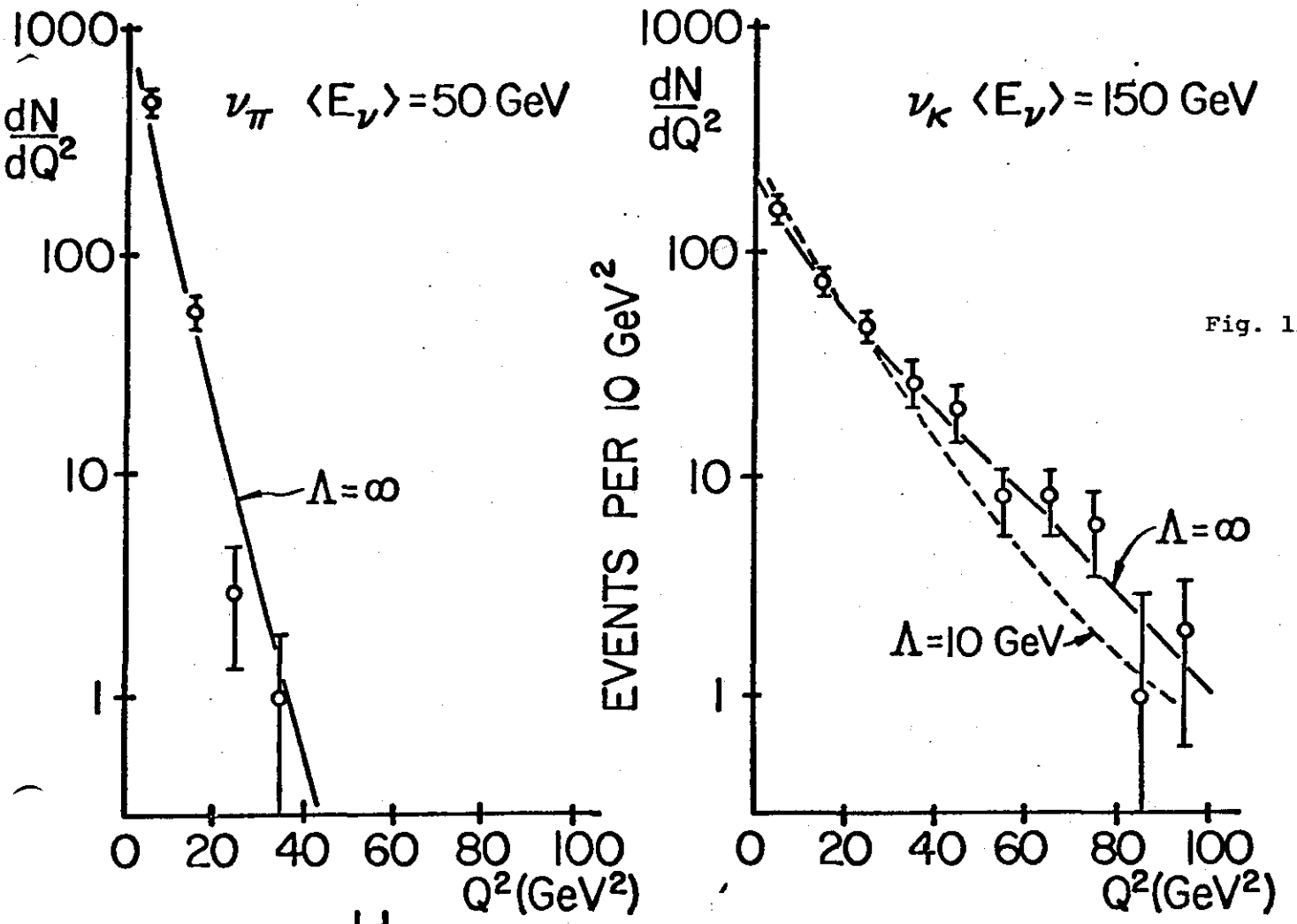
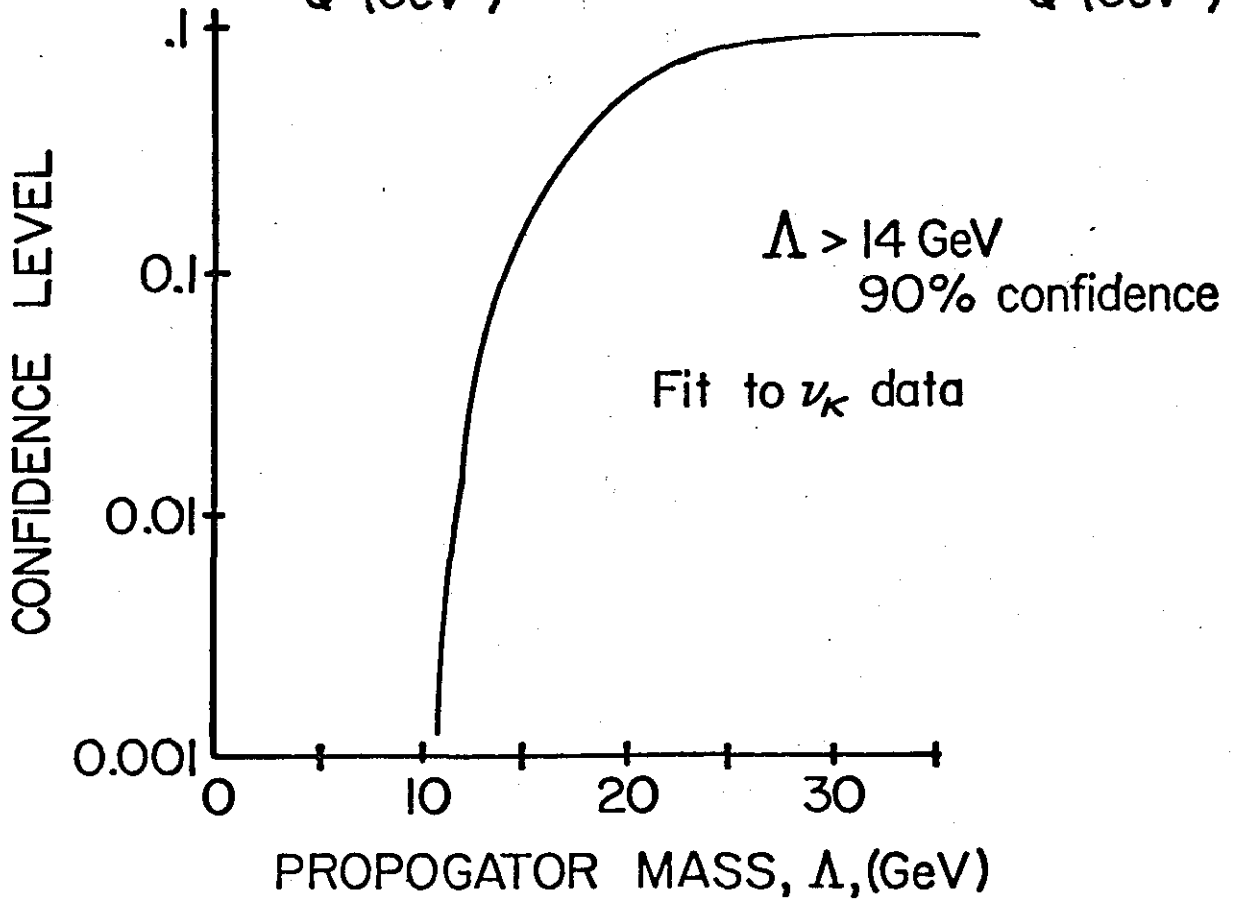


Fig. 12



(2) The neutrino charged current data shows no anomalous y-dependent behavior at the 30% level when comparisons are made between 50 GeV and 150 GeV incident energies. The large-Q^2 dependence follows the form predicted for neutrinos of 150 GeV at a level to rule out a 14 GeV/c^2 propagator mass.

(3) The large-y dependence of anti-neutrino events is consistent with the behavior expected from lower energy experiments. Both the size of the effect and the x-dependence of the effect are qualitatively similar to that observed by Gargamelle. (It should be note that precise comparisons with low energies should not be expected, particularly in the region of small x or x′ where Q^2 are small at low energy.)

(4) The small-y behavior of the HPWF anti-neutrino data is inconsistent with the requirements of charge symmetry in the region of small x. The Caltech-Fermilab anti-neutrino data at 50 GeV do not corroborate a violation of charge symmetry. In any case, such behavior would be unlikely to occur as a result of the production of high mass hadrons.

As recently as two years ago, experimentation in high-energy neutrino collisions was expected to be experimentation on charged-current interactions. We now see the field divided into three separate topics, with 0, 1, or 2 muons in the final state. The first and last are really new fields, and as such require no motivation. Their very existence fulfills in part the promise of new physics with high-energy neutrinos.

To see new physics in the "old" field, with a single final-state muon, is unquestionably more difficult. But we have come part-way there. We know now that the simple scaling and quark pictures predicted for high energy works at a qualitative level up to more than 100 GeV. The challenge is clear: to quantify this agreement to the highest energy at which it holds; meanwhile, to push on to even higher energies where the new physics can be seen clearly.

In this regard, Serphukov has recently begun neutrino experimentation, and the CERN SPS will be running within two years. The existing programs at FNAL are tooling up to do experiments with substantially improved statistical and systematic errors at even higher energy. New programs with the 15 foot bubble chamber at Fermilab are beginning now to produce results that complement in an important way the counter programs at existing energies. At the same time, serious work is proceeding to raise the energy of the FNAL machine. There is no question that the challenge has been accepted.

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