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# MEASUREMENTS OF NEUTRINO AND ANTINEUTRINO CROSS SECTIONS AT HIGH ENERGIES


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## ABSTRACT

The dependence of the neutrino total cross section $\sigma_\nu$ on neutrino energy has been measured up to 160 GeV. The data are consistent with a linear dependence with slope $(0.58 \pm 0.25) \times 10^{-38}$ cm$^2$/GeV. The ratio of the antineutrino to the neutrino total cross section $\sigma_{\bar{\nu}}/\sigma_\nu$ has been found to be approximately constant up to 70 GeV at a value which is consistent with the numerical value of 1/3 expected for the scattering of neutrinos and antineutrinos by relativistic pointlike spin 1/2 fermions.

We discuss here the observation of events of the types $\nu_\mu(\bar{\nu}_\mu)$ + nucleon $\rightarrow \mu^-(\mu^+)$ + hadrons, from which are obtained: (i) a measurement of the dependence of the neutrino total cross section $\sigma_\nu$ on neutrino energy $E_\nu$ up to 160 GeV, and (ii) measurements of the ratio of antineutrino to neutrino total cross sections $\sigma_{\bar{\nu}}/\sigma_\nu$ up to 70 GeV.

Details of the experimental arrangement were described previously.[1] Briefly, useful neutrino interactions occurred either in a liquid scintillator ionization calorimeter, or in the first section of an iron magnetic spectrometer located immediately downstream of the calorimeter. For all events the vector momentum and sign of charge of the secondary muon were measured in the magnetic spectrometer. In the temporary absence of other information we assume that negative and positive muons are produced in neutrino and antineutrino interactions, respectively. For interactions occurring in the ionization calorimeter the energy of the hadron cascade, $E_h$, was also measured. The detector was activated by either of two coincidence modes: (i) a muon traversing the entire length of the magnetic spectrometer, or (ii) a muon traversing at least the first section of the spectrometer in conjunction with various preset minimum depositions of energy in the calorimeter. Data were taken with primary proton energies $E_p$ of 300 and 400 GeV.

We plot in Fig. 1 the observed distributions in momentum $p_\mu$ and angle $\theta_\mu$ for muons of negative and positive charge, combining data at proton energies of 300 and 400 GeV. Shown also in Fig. 1 are Monte Carlo distributions calculated by assuming scale invariance and form factors obtained from electroproduction[2] and low energy neutrino data.[3] The calculation includes the geometric and magnetic-focusing properties (detection efficiency) of the detector, and an incident neutrino or antineutrino spectrum.[4] The good agreement between the observed and predicted distributions in $p_\mu$ and $\theta_\mu$ indicates

the approximate validity of the combined input to the Monte Carlo calculation.

In Figs. 2a and b are shown the observed and Monte Carlo calculated distributions in hadron energy $E_h$ for interactions that occur in the ionization calorimeter. The agreement on average between the data and the Monte Carlo calculations validates this method[5] of measuring $E_h$. Moreover, Figs. 1 and 2b taken together, indicate the average accuracy with which the energy of an incident neutrino $E_\nu$ may be determined from the sum $E_h + E_\mu$ for a given event. We estimate the mean accuracy in $E_\nu$ to be better than ± 20%.

Shown in Fig. 2c is the observed event distribution in $E_\nu$, after correction for detection efficiency only. This directly yields values of the integrals $H_\nu \equiv \int_{E_i}^{E_j} \sigma_\nu(E_\nu)\, N(E_\nu)\, dE_\nu$ in the intervals $(E_j - E_i)$, where $N(E_\nu)$ is the neutrino flux. Note that no assumption about the energy dependence of the cross section is involved in extracting the values of $H_\nu$ from the event distribution. Taking $N(E_\nu)$ from particle production data and a semi-empirical model[4], we obtain the dependence of $\sigma_\nu$ on $E_\nu$ which is shown in Fig. 3a. The data are consistent with a linear dependence on $E_\nu$ up to 160 GeV.

The absolute values on the cross section axis in Fig. 3a were obtained by using events of the types $\nu_\mu + n \rightarrow \mu^- + p$ (quasielastic) and $\nu_\mu$ + nucleon $\rightarrow \mu^- + N^*$ (resonance production). The shapes of the observed distributions in $q^2$ and $W^2$, at low $q^2$ and $W^2$, which are shown in Figs. 3b and 3c, indicate that events of these types are directly recognized in the detector. ($W^2$ is the squared invariant hadron mass). Among the events that comprise Fig. 3a there is a corrected total of 13 events with: 12 GeV $\leq E_\nu \leq$ 45 GeV, $q^2 \leq 1$ GeV$^2$ and $W^2 \leq 3.5$/GeV$^2$. The corrected total number of events in the same interval in $E_\nu$ is 204, and the measured mean energy of these events is 27.2 GeV. The sum of the cross sections for quasielastic scattering and resonance production can be estimated from low energy neutrino data and

phenomenological calculation[6,7] as $(1.0 \pm 0.3) \times 10^{-38}$ cm$^2$/nucleon, approximately independent[8] of $E_\nu$ above a few GeV. The absolute value of the slope $\alpha_\nu$ of the straight line in Fig. 3a is then determined to be $(0.58 \pm 0.25) \times 10^{-38}$ cm$^2$/GeV. To emphasize the dependence of this result on the low energy cross section data we show in Fig. 3d the relation of $\alpha_\nu$ to the sum of the partial cross sections. For comparison, the value of $\alpha_\nu$ calculated by assuming CVC and chiral symmetry, and using electroproduction data[2] is also shown in Fig. 3d. A value of $\alpha_\nu = (0.74 \pm 0.02) \times 10^{-38}$ cm$^2$/GeV has previously been measured[3] for neutrino energies between 1 and 10 GeV.

Now, taking $\sigma_\nu = \alpha_\nu E_\nu$ and $\sigma_{\bar\nu} = \alpha_{\bar\nu} E_{\bar\nu}$, and using the corrected event distributions as functions of incident energy, we find values of the ratio $\alpha_{\bar\nu} I_{\bar\nu}/\alpha_\nu I_\nu$ in specified energy intervals, where, e.g., $L_{\bar\nu} = \int_{E_i}^{E_j} N_{\bar\nu}(E_{\bar\nu})\, E_{\bar\nu}\, dE_{\bar\nu}$. To determine the ratio $I_\nu/I_{\bar\nu}$ we again use particle production data and a semi-empirical model.[4] Fig. 4a shows the ratio $\alpha_{\bar\nu}/\alpha_\nu$ as a function of $E_\nu$ up to 70 GeV. Above that energy neutrinos and antineutrinos from charged kaon decay contribute importantly to the interaction rates and, since the uncertainties in secondary kaon production are large, we do not yet attempt to specify $\alpha_{\bar\nu}/\alpha_\nu$ beyond 70 GeV.

If we combine all of the observed neutrino and antineutrino data by taking the same distribution in $E_\nu$ for events in the iron as for events in the liquid scintillator, we obtain $\alpha_{\bar\nu}/\alpha_\nu = 0.34 \pm 0.03$ at a mean neutrino energy of 27 GeV, where the error is purely statistical. To emphasize the dependence of $\alpha_{\bar\nu}/\alpha_\nu$ on $I_\nu/I_{\bar\nu}$, we show the relationship between these ratios and their uncertainties in Fig. 4b. Clearly, improved measurements of $I_\nu/I_{\bar\nu}$ are necessary for high precision determinations of $\alpha_{\bar\nu}/\alpha_\nu$.

In summary, within experimental error, we reach the following conclusions from the data presented here.

(i) The neutrino total cross section is rising approximately linearly with neutrino energy up to 160 GeV. A linear rise was initially predicted by Bjorken[9] as a consequence of scale invariance.

(ii) In view of conclusion (iii) below, the value $(0.58 \pm 0.25) \times 10^{-38}$ $cm^2$/GeV of the slope $\alpha_\nu$ of the linear rise confirms the conserved vector current (CVC) hypothesis relating weak and electromagnetic transition amplitudes.

(iii) The ratio of the antineutrino to the neutrino total cross section $\alpha_{\bar{\nu}}/\alpha_\nu$ is approximately 1/3 and constant up to an energy of 70 GeV. A similar value has been reported for the energy region below 10 GeV by CERN.[3] This is of particular interest at the higher energies because of the deep inelasticity of most of the interactions. These properties are consistent with a parton model[10] of nucleon constituents in which the partons are relativistic and predominantly spin 1/2 fermions, not antifermions.

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## References and Footnotes

* Alfred P. Sloan Foundation Fellow, now at the University of Chicago, Chicago, Illinois 60637.

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1 A. Benvenuti et al, Phys. Rev. Letters 30, 1084 (1973).

2 We use an empirical fit to the data of G. Miller et al, Phys. Rev. D 5, 528 (1972); V. Barger, private communication.

3 D. H. Perkins, Proc. of the XVI International Conference on High Energy Physics, Chicago-Batavia 4, 189 (1972); T. Eichten et al, CERN preprint submitted to Physics Letters.

4 In the kinematic region of $\pi^{\pm}$ and $K^{\pm}$ production that contributes to the $\nu(\bar{\nu})$ flux ($p_{\perp} < 200$ MeV, $0.2 < x < 0.7$) hadronic scaling appears to obtain for protons on protons above 30 GeV. That region is moderately well fit by the semi-empirical model of Grote, Hagedorn and Ranft, CERN-Scientific Information Service-3000 (1970), which has been used as an interpolating tool. M. G. Albrow et al, Physics Letters, 40B, 136 (1972); L. G. Ratner et al, Phys. Rev. Letters 27, 68 (1971); A. Bertin et al, Physics Letters 38B, 260 (1972); many papers presented at the Fourth International Conference on High Energy Physics, Oxford (1972); F. T. Dao et al, NAL Report, NAL-CONF-73/31-Exp. 7200.037; S. Barish et al, NAL Report, NAL-CONF-73/25-Exp. 7200.141. Scaling behavior has also been verified for complex nucleus targets over the energy region 30 GeV $< E_p <$ 300 GeV; J. Pilcher et al, Proc. of the XVI International Conference on High Energy Physics, Chicago-Batavia 1, 252 (1972).

5 Conversion from the visible energy $E_{vis}$ to the total energy $E_h$ of the hadrons produced in the interaction is made via a response curve based

upon calculations of hadron cascades and several experimental check-points. See W. V. Jones, et al, Phys. Rev. D7, 2013 (1973); J. Ranft, Nucl. Inst. and Methods 81, 29 (1970); E. B. Hughes, et al, Nucl. Inst. and Methods 75, 130 (1969); R. C. Webb, et al, Princeton-Penn Accel. Rept. PPAR 26 (1970) (unpublished); W. Selove (private communication).

6 For quasielastic scattering and low mass resonances: I. Budagov et al, Lett. Nuovo Cimento 2, 686 (1969); W. A. Mann et al, Proc. of the XVI International Conference on High Energy Physics, Chicago-Batavia, 1972; T. Eichten et al, preprint submitted to Physics Letters; J. Campbell et al, Phys. Rev. Letters 30, 335 (1973); P. Schreiner and F. von Hippel, Phys. Rev. Letters 30, 339 (1973). Higher resonances: F. Ravndal, CALTECH Preprint 68-386 (1973).

7 D. Perkins and J. J. Sakurai independently pointed out to us that the value of $\sigma$(quasielastic) + $\sigma$(resonance production) used in reference 1 was too high. There we assumed and included larger cross sections for the higher resonances (although we inadvertently referred only to the $\Delta$). Since then the experimental values of $\sigma$(quasielastic) and $\sigma$($\Delta$ production) have decreased also.

8 T. D. Lee and C. N. Yang, Phys. Rev. Letters 4, 307 (1960); Phys. Rev. 119, 1410 (1960); 126, 2239 (1962); Y. Yamaguchi, Progr. Theoret. Phys. (Kyoto) 23, 1117 (1960); N. Cabibbo and R. Gatto, Nuovo Cimento 15, 304 (1960).

9 J. D. Bjorken, Phys. Rev. 179, 1547 (1969); J. D. Bjorken and E. A. Paschos, Phys. Rev. D1, 3151 (1970).

10 R. P. Feynman, Phys. Rev. Letters 23, 1415 (1969) and in Proc. of the Third Topical Conference on High Energy Collisions, Stony Brook, N. Y., (1969); J. D. Bjorken and E. A. Paschos, Phys. Rev. 185, 1975 (1969).

## Figure Captions

Fig. 1. Observed distributions (histograms) in muon momentum, $p_\mu$, and angle, $\theta_\mu$, for antineutrinos and neutrinos. Shown as continuous curves are the Monte Carlo calculated distributions normalized in area to the data.

Fig. 2. Observed (histograms) and Monte Carlo calculated distributions in hadron energy, $E_h$, for (a) antineutrinos and (b) neutrinos. (c) Event distribution in $E_\nu$ after correction for detection efficiency which is shown as the dashed line. Before correction there are 223 neutrino events.

Fig. 3. (a) Neutrino total cross section $\sigma_\nu$ vs $E_\nu$. (b) Distribution in $q^2$ for events with $W^2 \leq 4$ GeV$^2$. (c) Observed distribution in invariant hadron mass squared, $W^2$, for events with $q^2 \leq 1$ GeV$^2$. (d) Plot showing the dependence of the measured slope, $\alpha_\nu = \sigma_\nu/E_\nu$, on the sum of the partial cross sections $\sigma$(quasielastic) + $\sigma$(resonance production). The dashed line indicates the uncertainty in $\alpha_\nu$ due to $\sigma(N \to N^*)$.

Fig. 4. (a) Plot of $\alpha_{\bar{\nu}}/\alpha_\nu$ vs $E_\nu$. Values of $I_\nu/I_{\bar{\nu}}$ of 1.1, 1.5, 1.9 and 2.2 were used at $E_\nu$ = 10, 30, 50 and 70 GeV, respectively. (b) Dependence of $\alpha_{\bar{\nu}}/\alpha_\nu$ on $I_\nu/I_{\bar{\nu}}$. The errors shown on $\alpha_{\bar{\nu}}/\alpha_\nu$ in (a) and (b) are statistical only. The estimated uncertainty due to $I_\nu/I_{\bar{\nu}}$ is indicated by the dashed line in (b).

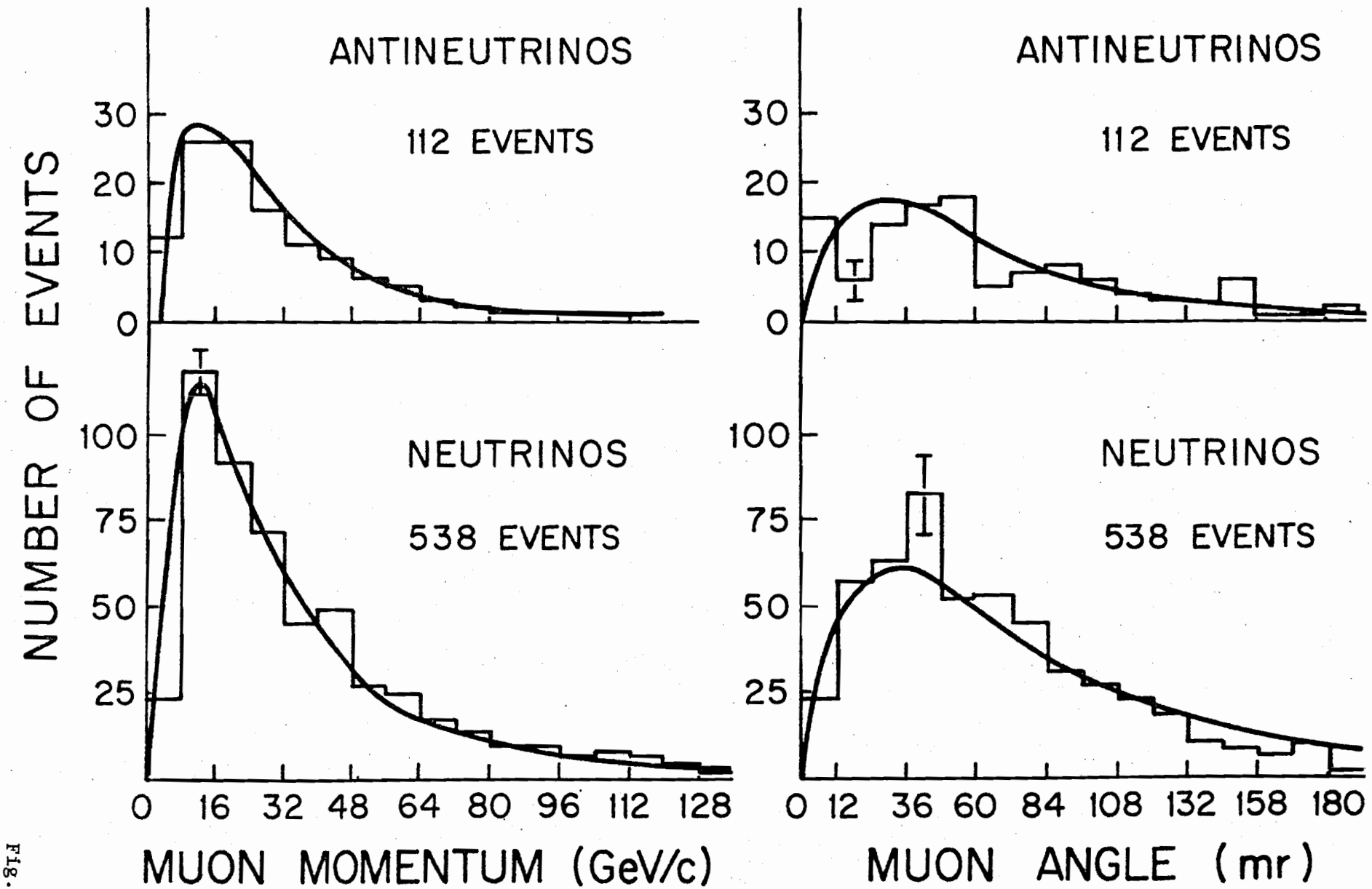
ANTINEUTRINOS
112 EVENTS
NEUTRINOS
538 EVENTS
NUMBER OF EVENTS
0
10
20
30
25
50
75
100
0 16 32 48 64 80 96 112 128
MUON MOMENTUM (GeV/c)
0 12 36 60 84 108 132 158 180
MUON ANGLE (mr)

Fig. 1

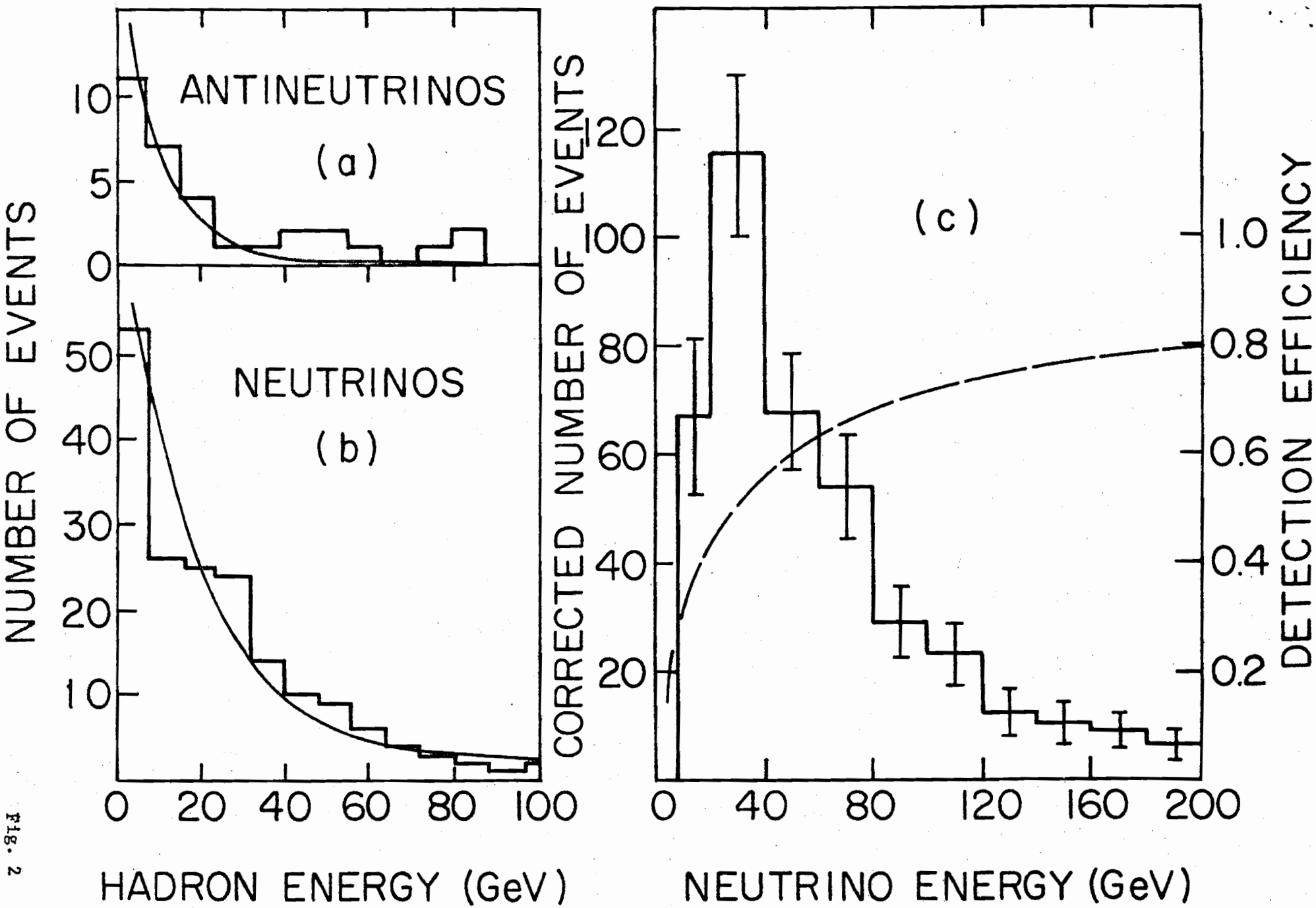
ANTINEUTRINOS
(a)
NEUTRINOS
(b)
(c)
NUMBER OF EVENTS
CORRECTED NUMBER OF EVENTS
DETECTION EFFICIENCY
HADRON ENERGY (GeV)
NEUTRINO ENERGY (GeV)
0
20
40
60
80
100
120
160
200
1.0
0.8
0.6
0.4
0.2

Fig. 2

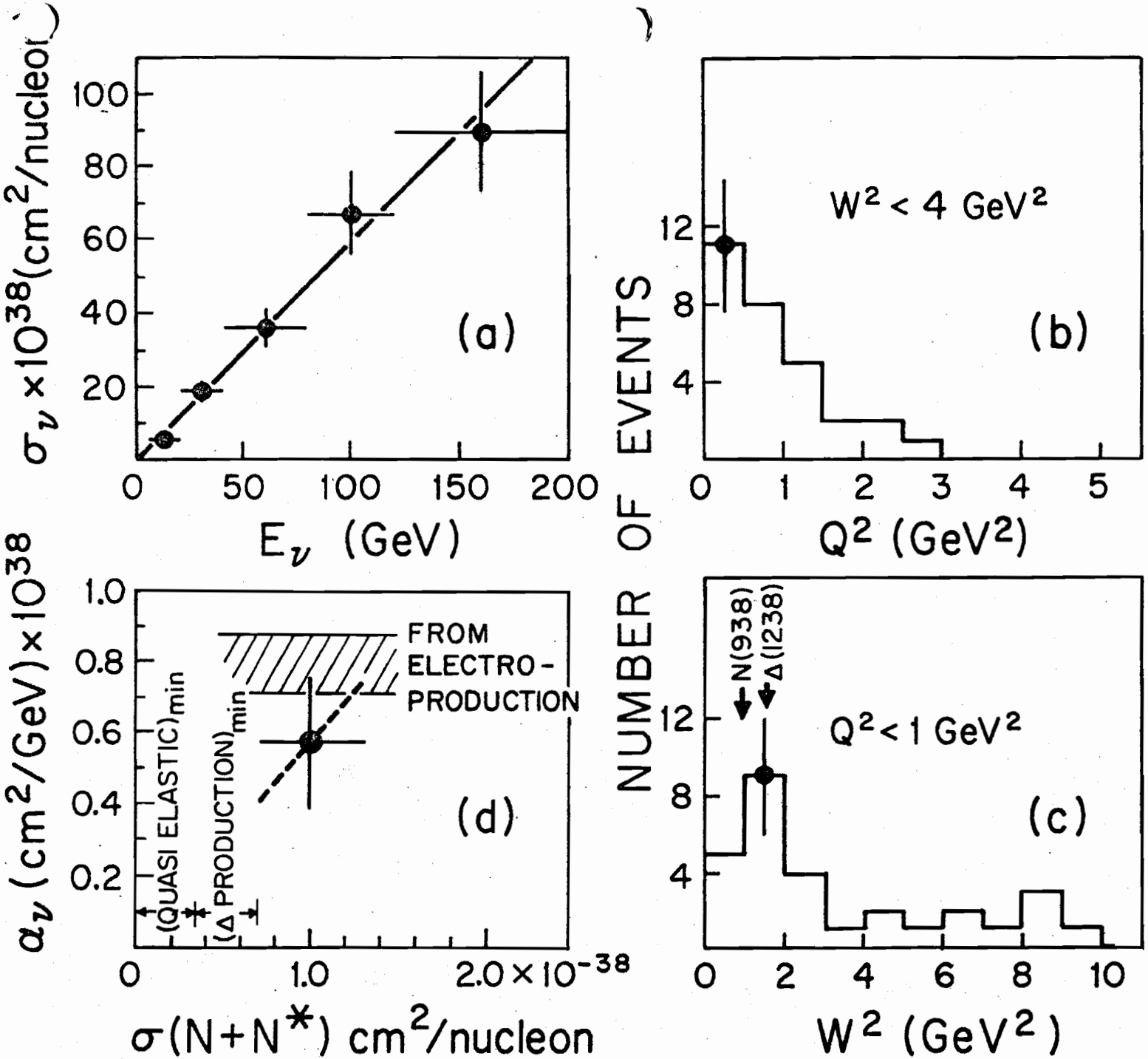
$\sigma_\nu \times 10^{38}$(cm$^2$/nucleon)
100
80
60
40
20
0
50
100
150
200
$E_\nu$ (GeV)
(a)
NUMBER OF EVENTS
$W^2 < 4$ GeV$^2$
12
8
4
0
1
2
3
4
5
$Q^2$ (GeV$^2$)
(b)
$\alpha_\nu$ (cm$^2$/GeV) $\times 10^{38}$
1.0
0.8
0.6
0.4
0.2
FROM ELECTRO-PRODUCTION
(QUASI ELASTIC)$_{min}$
($\Delta$ PRODUCTION)$_{min}$
(d)
0
1.0
$2.0 \times 10^{-38}$
$\sigma(N+N^*)$ cm$^2$/nucleon
N(938)
$\Delta$(1238)
$Q^2 < 1$ GeV$^2$
12
8
4
0
2
4
6
8
10
$W^2$ (GeV$^2$)
(c)

Fig. 3

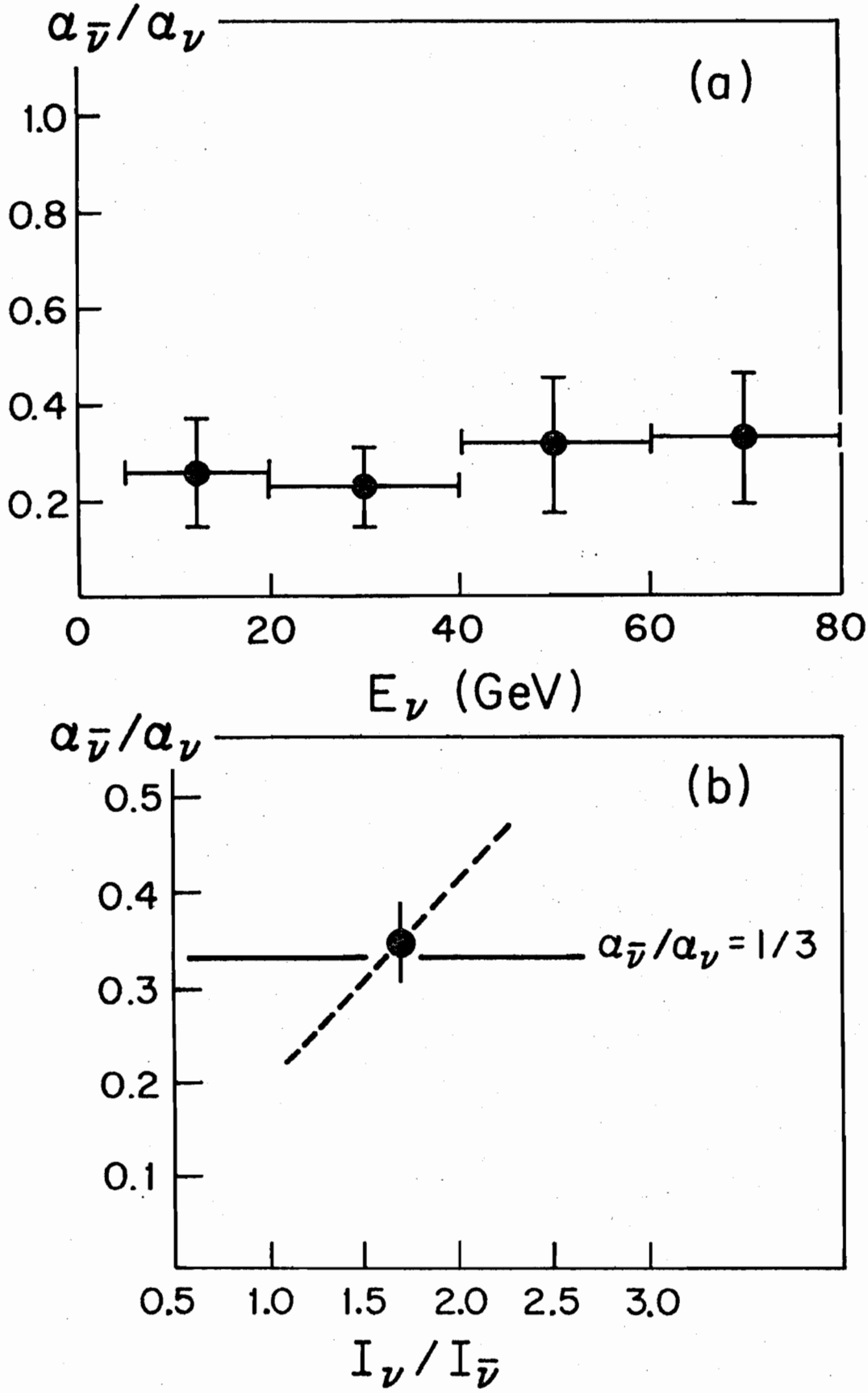
$\alpha_{\bar{\nu}}/\alpha_{\nu}$
(a)
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
$E_{\nu}$ (GeV)
$\alpha_{\bar{\nu}}/\alpha_{\nu}$
(b)
0.5
0.4
0.3
0.2
0.1
$\alpha_{\bar{\nu}}/\alpha_{\nu} = 1/3$
0.5
1.0
1.5
2.0
2.5
3.0
$I_{\nu}/I_{\bar{\nu}}$

Fig. 4