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NORMALIZED SMALL Y CROSS SECTIONS FOR NEUTRINOS AND ANTINEUTRINOS AT HIGH ENERGY

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ABSTRACT

We present results on flux-normalized neutrino and antineutrino cross-sections near y=0 from data obtained in the Fermilab narrow-band beam. We conclude that values of $\sigma_o = d\sigma/dy|_{y=0}$ are consistent with rising linearly with energy over the range $45 \leq E_\nu \leq 205$ GeV. The separate averages of ν and $\bar{\nu}$, each measured to 4%, are equal to well within the errors. The best fit for the combined data gives $\sigma_o/E = (0.719 \pm 0.035) \times 10^{-38}$ cm^2/GeV at an average E_ν of 100 GeV.

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Conventional V-A weak interaction theory, written in terms of the usual scaling variables x and y, predicts that at y=0 the neutrino-nucleon charged current cross-section at high energy is simply

$$\sigma_o^{\nu,\bar{\nu}} \equiv \left.\frac{d\sigma^{\nu,\bar{\nu}}}{dy}\right|_{y=0} = \frac{G^2ME}{\pi} \int F_2^{\nu,\bar{\nu}}(x)\, dx. \quad (1)$$

Here G is the weak coupling constant, M is the nucleon mass, E is the neutrino energy, and $F_2(x)$ is the nucleon structure function. Charge symmetry invariance for an isoscalar target would predict $F_2^{\nu}(x) = F_2^{\bar{\nu}}(x)$, implying that these neutrino and antineutrino cross-sections are equal ($\sigma_o^{\nu} = \sigma_o^{\bar{\nu}}$).

We have made measurements of σ_o^{ν}, $\sigma_o^{\bar{\nu}}$ on an iron target using a high energy ($45 < E < 205$ GeV), narrow-band neutrino beam. All events with $y < 0.2$ were used, with a small correction based on the shape of the y-distribution applied to extrapolate the data to y=0. This small y cross-section, where little energy is transferred to the nucleon, is relatively insensitive to hadronic thresholds. In practice, we might expect small deviations from either equality at fixed E and/or linearity versus E due to (a) the Cabbibo angle ($\sin^2\theta_c \sim .05$) (b) scale breaking at low or high Q^2, (c) threshold effects due to charmed-particle production, (d) neutron-proton excess in the iron target, or (e) some fraction of the cross-section that is energy independent (e.g., quasi-elastic). Estimates of these effects indicate that cancellations will occur, so that the net effect should be of order 5% or less over the energy range of this

experiment. Much larger deviations from equality, or substantial energy dependence, would indicate that important modifications to the V-A structure of charge-current weak interactions are necessary. Some interpretations[1] of existing data[2] have suggested such anomalous behavior.

This experiment utilized the Fermilab narrow-band neutrino beam.[3] The narrow-band technique was first applied to an earlier measurement[4] of total neutrino and antineutrino cross-sections by this group. As shown therein,[4] momentum selected pions and kaons entered a 350 m long evacuated pipe where some fraction of them decayed, producing neutrinos which were detected some 500 m further downstream. The neutrino flux at the detector was calculated directly from the measured number of π's and K's in the decay pipe, the location of the detector relative to the decay region, the particle momenta and lifetimes, and two-body decay kinematics.

Improvements which have been made since the earlier run include: upgrading the primary proton energy from 300 GeV to 400 GeV, adding a second large ionization chamber in the decay region, added redundancy in the ion chamber calibration, and improved $\pi/K/p$ ratio measurements. A significantly longer run of about 2×10^{18} incident protons at 400 GeV allowed us to double our highest neutrino and antineutrino energies and obtain over an order of magnitude increase in the number of observed events.

During this run the secondary transport was tuned to accept positive secondaries at mean momenta of 130, 190, and 250 GeV

and negatives at 130, 190, and 230 GeV. Each of the narrow-band beam settings provided two distinct neutrino energy bands (Fig. 1).

The total intensity of the secondary hadron beam was measured by ionization chambers at two points inside the decay pipe. Their linearities were better than 1% over the range of intensities used in the experiment, and their relative response was stable to ±1% at each fixed secondary beam setting. Absolute measurements of the total secondary intensity by the two ion chambers, after corrections for beam containment and backgrounds, agreed on average to 5%. Steering of the secondary beam was continuously monitored so that the neutrino beam centroid was stable to 2 cm at the neutrino detector.

By transporting a 200 GeV primary proton beam through the entire secondary transport system (without target) and the decay region, the ion chambers were calibrated against a secondary emission monitor (SEM) and a simultaneous foil irradiation. After correcting for absorption in the air of the transport system (9%), this calibration agreed to 2% with one made against individually counted particles.

Particle fractions of pions, kaons, and protons were determined[5] to estimated accuracies of (1-5)%, (3-7)%, and (1-2)%, respectively, at various secondary energies. Combining these errors with those of the total intensity measurements, we obtain point-to-point flux errors of (5-9)%. This error does not include an overall flux calibration error, estimated to be 4%.

The Caltech-Fermilab neutrino detector[4] was used to observe and record the neutrino events. The detector consisted of an instrumented steel target-calorimeter, followed by an iron toroidal spectrometer. The apparatus was triggered by either (1) a muon traversing scintillation counters upstream and downstream of the magnet (muon trigger), or (2) a significant energy deposition in the target-calorimeter (hadron trigger). The efficiency of the muon trigger was empirically determined[6] to be 97%. The analysis which includes those events in which the muon did not traverse the magnet will be described in a later letter.[6]

For those events with the muon track through the magnet, the hadron energy (E_h), the muon energy (E_μ), and the muon angle (θ_μ) were measured. Events were required to originate inside the fiducial volume (1.27 m x 1.27 m x 10 m centered 8.3 m upstream of the 1.5 m diameter toroidal magnet), and to have muons of the correct sign which go forward in the detector. A subtraction (~5%) was made for the measured residual background from neutrinos not originating in the decay pipe.

A comparison between the observed total energy ($E_{sum} = E_\mu + E_h$) and the known neutrino beam energy distribution provided an important check on the energy calibration. Separate calibrations of muon and hadron energy were made by comparing the measured energies of events with small or large hadron energies against the known beam energy. Calibrations obtained at different beam settings agreed with each other to better than 5%.

Figure 1 shows the observed total energy distributions at the +190 GeV secondary setting. The value of E_{sum} for an event, as well as the transverse vertex position, permitted us to determine whether that event resulted from a pion or kaon neutrino. The frequency of event misidentification was estimated from a detailed Monte Carlo study. We include a systematic error of (1-8)%, depending on the neutrino energy, for such effects.

The requirement that muons traverse the magnet limited acceptable muon triggers to relatively small polar angles. However, an observed event at a fixed target location can be utilized to determine the fraction of missed events with the same polar angle by executing an azimuthal rotation through 2π, and calculating the fraction of azimuthal angles in which the muon would miss the toroid. Events, after correcting for this azimuthal efficiency, have full polar efficiency for $\theta_\mu < 110$ mrad. In our energy range, all events with $y < 0.2$ are constrained by kinematics to fall in this polar region.

The low y cross-section per nucleon was calculated from the relation $\sigma_o = CN/FT\Delta$ where N is the number of efficiency corrected events with $y < 0.2$, F is the total number of incident neutrinos, T is the number of target nucleons, Δ is the y interval ($\Delta = .2$), and C is a correction factor for the shape of the y distribution. The correction factors were $C_\nu = 1.018$, 1.036 and $C_{\bar{\nu}} = 1.204$, 1.179 for $E > 100$ GeV and $E < 100$ GeV respectively.[7]

Figure 2 shows the measured data points for σ_o/E versus E for both neutrinos and antineutrinos. For fitting purposes,

we assume $(\sigma_o/E)_{\nu,\bar{\nu}} = s_{\nu,\bar{\nu}} + E\, t_{\nu,\bar{\nu}}$, with E in GeV. For exact ν-$\bar{\nu}$ equality, we expect $s_\nu = s_{\bar{\nu}}$ and $t_\nu = t_{\bar{\nu}}$. A strict linear dependence of σ_o on E would, in addition, give $t_\nu = t_{\bar{\nu}} = 0$. The best fits are $s_\nu = .77 \pm .06$, $t_\nu = -(.66 \pm .65) \times 10^{-3}$, and $s_{\bar{\nu}} = .75 \pm .06$, $t_{\bar{\nu}} = -(.24 \pm .50) \times 10^{-3}$ in units of 10^{-38} cm^2/GeV. These values are consistent with being both equal and independent of energy. However, a small (~15%) decrease over this energy range cannot be ruled out. The cross-section at y=0, averaged over the energies of the experiment, is

$$\sigma_o/E = (.719 \pm .035) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV} \qquad (2)$$

at an average incident neutrino energy of about 100 GeV. The latter error includes an additional 4% contribution from the flux calibration folded in quadrature.

Using Eqs. (1) and (2), we calculate the integrated structure function, $\int F_2^{\nu}(x)\, dx = 0.46 \pm 0.02$. The integral determined in this manner is insensitive to assumptions about relationships between the structure functions (e.g., Callan-Gross relation). In constituent models, $\int F_2^{\nu}(x)\, dx$ represents the fraction of the momentum carried by interacting constituents.[8] Previous calculations[9] using total cross-sections and assuming the Callan-Gross relation are in agreement with the more direct measurement reported here.

In conclusion, we find that σ_o is consistent (to 15%) with rising linearly with energy over the range $45 \leq E \leq 205$ GeV. The average values of σ_o^{ν} and $\sigma_o^{\bar{\nu}}$ are equal, well within the

4% errors on each. We find no evidence for any violation of charge symmetry invariance.

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REFERENCES

[1]D. Cline, in Proceedings of the International Conference on High Energy Physics, Palermo, Italy, June 1975; C. Llewellyn Smith, in Proceedings of the Interactions at High Energies, Stanford, California, 1975, edited by W. T. Kirk, (Stanford Linear Accelerator Center, Stanford, Calif., 1975), p. 709.

[2]B. Aubert et al., Phys. Rev. Lett. 33, 984 (1974).

[3]B. C. Barish et al., Fermilab Proposal E-21, 1970 (unpublished) and P. Limon et al., Nucl. Instrum. and Methods 116, 317 (1974).

[4]B. C. Barish et al., Phys. Rev. Lett. 35, 1316 (1975).

[5]B. C. Barish et al., CALT 68-611 (to be submitted for publication); Particle fractions were measured in separate runs at lower incident proton intensities using a differential Cerenkov counter. Background levels in the differential curve (from π, μ, e) were explicitly measured by additional counters in coincidence.

[6]B. C. Barish et al., CALT 68-605 (to be submitted for publication).

[7]We have calculated the correction factors using antiquark contents $\alpha = 0.093$ ($E < 100$ GeV) and $\alpha = 0.186$ ($E > 100$ GeV) obtained from our measured values of $\langle y \rangle_{\bar{\nu}}$ and σ_o/σ_{tot}; B. C. Barish et al., CALT 68-606 (to be submitted for publication).

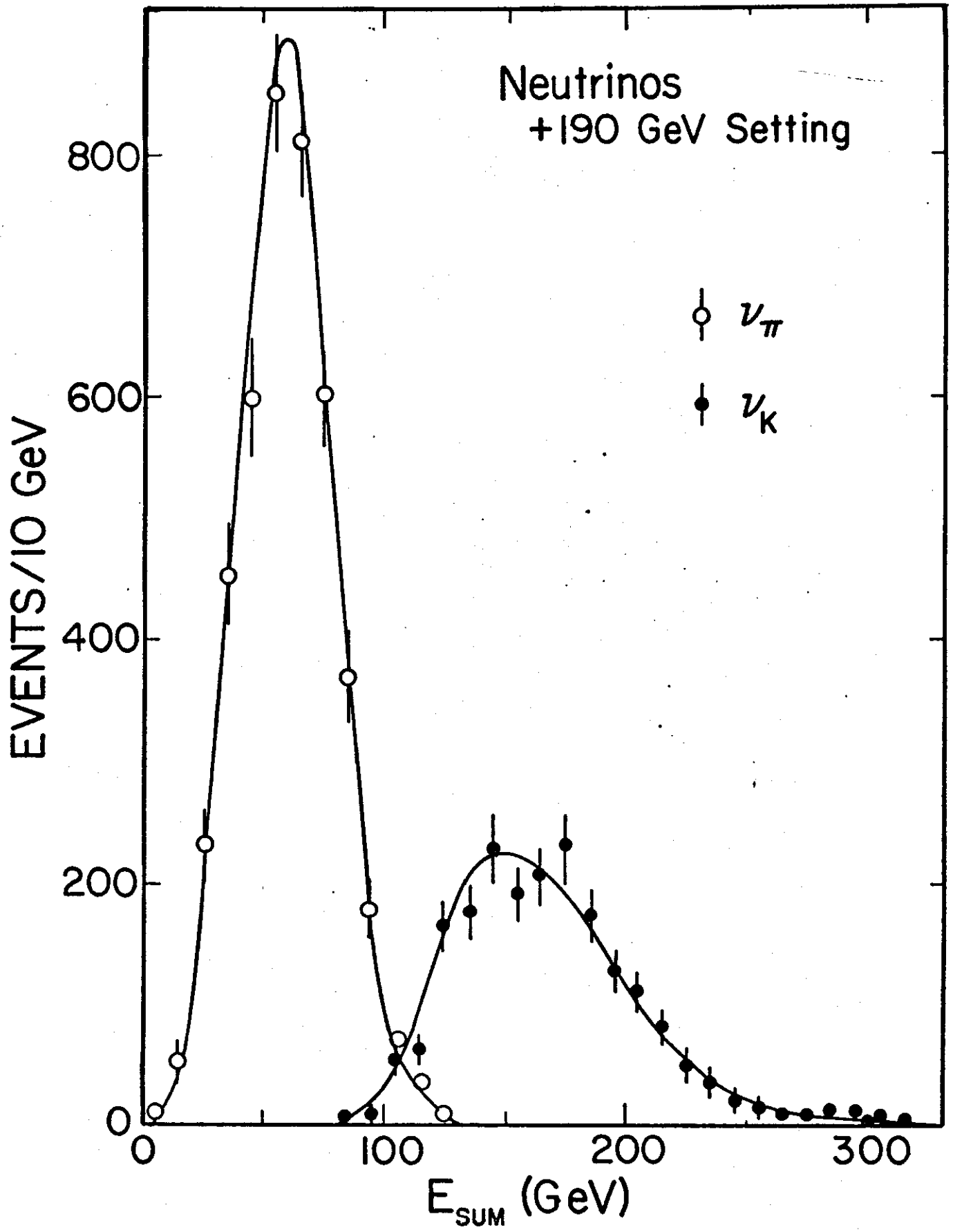
[8]A comparison of $\int F_2^{\nu}(x)\,dx$ with $\int F_2^{eD}(x)\,dx$ at similar four-momentum transfers ($Q^2 \sim 5\ \mathrm{GeV}^2$) yields a measure of $\langle e_q^2 \rangle$, the mean-squared charge of the constituents. Our value of $\int F_2^{\nu}(x)\,dx$ agrees with that expected for scattering from fractionally charged constituents, given the present errors on the eD measurement. See Ref. 9.

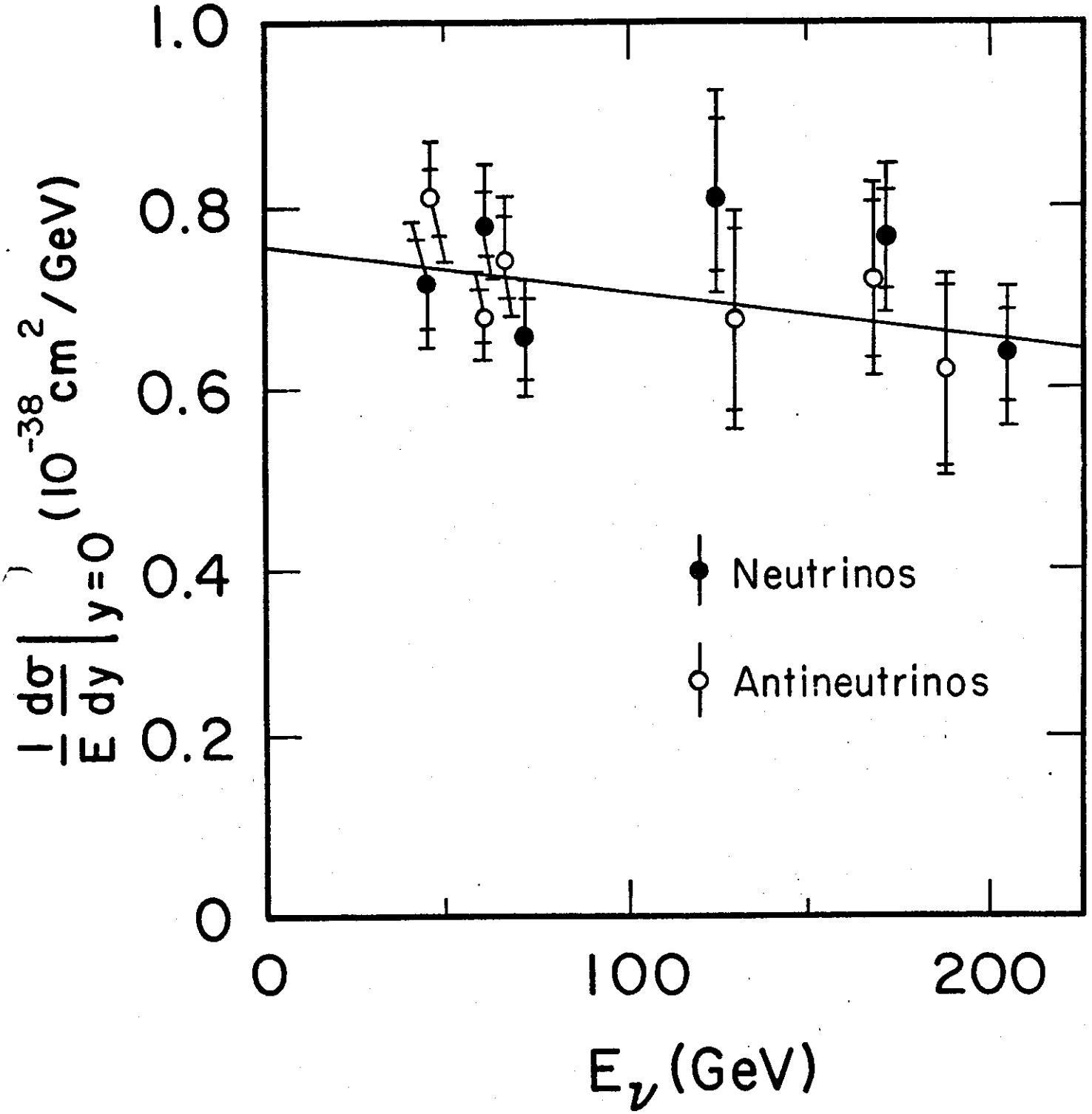
[9]H. Dedan et al., Nucl. Phys. B85, 269 (1975).

FIGURE CAPTIONS

Fig. 1: Measured ν total energy distribution for events satisfying the muon trigger at the +190 GeV secondary setting. Events in the energy distribution were separated into ν_π, ν_K using an algorithm involving the transverse vertex position. The smooth curves are Monte Carlo calculations which include the beam and experimental resolutions.

Fig. 2: σ_o/E for neutrinos and antineutrinos versus energy. The inner error bars are statistical only (corresponding to a total of 2385 ν and 2157 $\bar{\nu}$ events). The outer bars include systematic errors, primarily due to individual flux measurement, folded in quadrature. The best two parameter fit is shown, and gives s = (.75 ± .04), t = -(.37 ± .39) x 10^{-3}. The errors do not include an overall calibration error, estimated to be 4%.


Neutrinos
+190 GeV Setting
ν_π
ν_K
EVENTS/10 GeV
800
600
400
200
0
0
100
200
300
E_{SUM} (GeV)


1.0
0.8
0.6
0.4
0.2
0
0
100
200
$\frac{1}{E}\frac{d\sigma}{dy}\Big|_{y=0}$ (10^{-38} cm^2/GeV)
E_ν (GeV)
Neutrinos
Antineutrinos