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DIFFERENTIAL CROSS-SECTIONS FOR INCLUSIVE NEUTRAL CURRENT INTERACTIONS AT HIGH ENERGIES*

F. S. Merritt†, B. C. Barish, J. F. Bartlett, A. Bodek††, K. W. Brown, D. Buchholz†††, F. Jacquet$^{\Phi}$, F. J. Sciulli, L. Stutte$^{\Phi\Phi}$, and H. Suter$^{\Phi\Phi\Phi}$

California Institute of Technology, Pasadena, California 91125

and

H. E. Fisk and G. Krafczyk

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Abstract

We present measurements of the hadron energy distributions for the reactions $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu})$ + hadrons at high energy. The directly observed partial NC/CC ratios for $E_h > 12$ GeV are $R_{\nu}^{P} = 0.28 \pm .03$ and $R_{\bar{\nu}}^{P} = 0.35 \pm .11$.

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† Now at Stanford University, Stanford, California.

†† Now at the University of Rochester, Rochester, New York.

††† Now at Northwestern University, Evanston, Illinois 60201.

Φ On leave of absence from Ecole´ Polytechnique, Paris, France.

ΦΦ Now at Fermi National Accelerator Laboratory, Batavia, Illinois 60510.

ΦΦΦ Swiss National Fund for Scientific Research Fellow.

There is now substantial experimental evidence[1,2,3] for deep inelastic neutrino interactions that occur with no muon in the final state, but with energy carried away by a non-interacting neutral, presumably a neutrino.

$$\nu_\mu \ (\bar{\nu}_\mu) + N \rightarrow \nu_\mu \ (\bar{\nu}_\mu) + \text{hadrons} \tag{1}$$

The existence of these neutral current reactions was predicted[4] on the basis of a specific model. Within the context of this model, the reaction rates are determined by a single parameter, $x_w = \sin^2\theta_w$, where θ_w is commonly called the Weinberg angle. Recently, there have been somewhat different theoretical conjectures[5] as to the origins and underlying mechanisms for neutral currents, which predict somewhat different physical behavior for the processes.

We report in this paper the results from an experiment designed to yield information on the inelasticity distributions for the neutral current reactions. If the energy is such that the scale of the process (1) is set by the incident neutrino energy, the cross-sections will be of the form

$$\frac{d\sigma}{dE_h} = \frac{G^2M}{\pi} C_o f(E_h/E); \quad \frac{d\bar{\sigma}}{dE_h} = \frac{G^2M}{\pi} C_o \bar{f} \ (E_h/E) \quad . \tag{2}$$

where E_h = hadronic energy, E = incident neutrino energy, G = Fermi constant, C_o is some constant and M = target nucleon mass. These inelasticity functions f(y), $\bar{f}$(y) are the crucial measurements, in that their forms and relative magnitudes reflect the Lorentz structure of the neutral current and their absolute magnitudes are determined by the neutral current coupling.

The goal of this experiment was to provide measured values for these neutrino and anti-neutrino functions (2), with as little reliance as possible on <u>a priori</u> assumptions regarding the underlying mechanism. This goal is not easily achieved, however, because in reaction (1) no incident particle can be directly seen, and only the outgoing hadronic system is observable. To accomplish it, certain independently determined information

is necessary; principally, (1) knowledge of the incident neutrino energy; and (2) good separation of neutrino and antineutrino interactions. These were provided here by the use of the Fermilab narrow-band neutrino beam[6], tuned in turn to positive and negative hadrons of mean energy 170 GeV. Figure 1 shows the calculated energy distributions normalized to unit area, for the neutrino fluxes incident onto the apparatus. These spectral shapes depend mainly on the optical settings of the beam and only secondarily on π/K production spectra by 300 GeV protons. The charged current events taken simultaneously[7], in which all energy is measured, corroborate the shapes of these distributions.

Neutrinos originating upstream of the decay pipe present a serious background for the measurement of $\nu(\bar{\nu})$ induced neutral current distributions. This "wide-band" component presents a special problem because it contains both neutrinos and antineutrinos. In addition, this spectrum, which is peaked at low energy, depends directly on uncertain details of hadronic production at the proton target. Because of these difficulties, we have measured this background directly and made a statistical subtraction from the data. This was accomplished by running the experiment for approximately one-third of the data-taking with the hadron beam absorbed just prior to the entrance of the decay pipe so that only wide band events were produced during this time. The measured magnitude of this wide band neutral current background (8% for ν, 38% for $\bar{\nu}$) relative to the narrow band neutral current signal was about twice the value estimated by thin target flux calculations.

Neutral current events were collected in the Caltech-Fermilab detector[6] simultaneously with charged current events which have been described in a previous letter[7]. An event was recorded whenever more than 12 GeV of hadron energy deposition was sensed in coincidence with the 1 msec beam spill. The separation of charged-current events ($\nu_\mu + N \rightarrow \mu^- +$ hadrons) from neutral current events was accomplished later by exploiting the difference in penetration

in the steel target between the charged secondaries for a neutral current event and a muon in a charged current event. The technique was essentially identical to that utilized in a previous experiment by the authors[3]. The raw neutral current data sample consisted of those events wherein the most penetrating particle downstream of the interaction point traversed less than 1.6 meters of steel. There were 1033 ν_μ events and 239 $\bar{\nu}_\mu$ events in this raw sample. The raw charged-current sample, with events of longer penetration, was retained as a control sample. This division retains some contamination of the neutral current raw data from charged current events in a limited kinematic range, i.e. those with muon angle greater than about 225 mrad and those with muon energy less than about 2.4 GeV. The subtraction of this charged-current remnant will be addressed in more detail later.

The raw data sample was first corrected for the measured wide-band background component (described previously) and for background triggers due to cosmic rays impinging on the apparatus simultaneously with the beam. The latter (7% for ν, 14% for $\bar{\nu}$) was also directly measured utilizing a second beam gate separated in time from the actual beam spill time. Other corrections, including those due to errors in determining the interaction point, penetration of high energy showers past the 1.6m cutoff, and interactions of electron-type neutrinos were also made at this time. These latter (each amounting to less than 4% for both ν and $\bar{\nu}$) were considerably smaller effects than those from wide-band background or cosmic ray contamination. The resulting data samples, it should be emphasized, are purely separated neutrino and antineutrino events from neutrinos of known mean energy within the statistical limitations of the various subtractions.

The problem of mis-identified charged current events is illustrated in Figure 2. It shows the approximate acceptance (curve a) for recognizing a

secondary muon from 60 GeV neutrino interactions using the penetration requirement described previously. This efficiency is plotted against the scaling variable y. The identification problem arises primarily because muons of large polar angle (θ) exit the apparatus transversely before penetrating the minimum longitudinal distance. However, for muons with polar angle, θ, less than 300 mrad, the effect of this geometrical acceptance can be measured directly from the data by rotating the azimuthal angle ϕ of each recognized CC event through 2π, and calculating the fraction of "missed" muons with the same θ. This procedure, which assumes only that the cross-section is independent of azimuth, statistically corrects for CC contamination with $\theta \leq 300$ mrad.

The remaining contamination (above curve b), typically involving charged current events with $y \geqslant 0.9$, depends on the x-distribution for charged currents. This is of necessity an extrapolation of our present knowledge, which is summarized in a recent letter[7] by the authors. In that communication, various models (e.g. scaling, non-scaling, b-quark production) for the charged current are deemed possible; each of these was utilized to provide an estimate of this charged current contamination to the neutral current sample. The correction actually used involved removal of events from the neutral current sample equal to (26.5 ± 2.3)% for neutrinos and (11.5 ± 3.5)% for antineutrinos, and adding these to the charged-current sample. The larger percentage effect for neutrino events reflects their larger charged-current cross-section at large y. The larger error for antineutrino events reflects their greater theoretical and experimental uncertainty at large y. The quoted error indicates the largest deviation from the quoted correction over the entire set of charged-current models treated in reference 7, with fitted parameters in an acceptable range.

The corrected hadron energy distributions for both neutral and charged-current events are shown in Figure 3. They are normalized to facilitate fits

for $f(y)$, $\bar{f}(y)$ in equation (2). In the experiment, the flux was not measured independently, so we have chosen to normalize to charged-current data. The least controversial region of the charged-current cross-section is at small values of hadron energy, where the neutrino and antineutrino cross-sections at the same energy are predicted by charge-symmetry to be approximately equal. The hadron spectra for CC events were measured separately for pion and kaon neutrinos near $E_h = 0$ in this experiment with events from a separate (muon) trigger[7], and form the normalization used for Figure 3. The ordinate (F) represented, therefore, the ratios

$$F(E_h^m) = \frac{d\sigma^{NC}}{dE_h} \Big/ \left.\frac{d\sigma^{CC}}{dE_h}\right|_{E_h^m = 0}$$

The experimental distributions of Figure 3 get contributions from pion and kaon neutrinos: $F(E_h^m) = F_\pi(E_h^m) + F_K(E_h^m)$ where, for example, for pion neutrinos

$$F_\pi(E_h^m) = a_\pi \int \rho_\pi(E_\nu)\, dE_\nu \int R(E_h^m, E_h)\, f(E_h/E_\nu)\, dE_h,$$

a_π is the relative contribution to charged currents at $E_h = 0$ from pion neutrinos, ρ_π is the flux distribution shown in Figure 1, and $R(E_h^m, E_h)$ is the resolution function for hadron energy measurement[8]. The functions f and $\bar{f}$ represent the physics functions of equation (2). The relative contributions to $F(E_h^m)$ from ν_π/ν_K are $a_\pi/a_K = .856/.144$ for neutrinos and $.966/.034$ for antineutrinos. The overall relative $\nu - \bar{\nu}$ uncertainty in the normalization is about 15%. The curves through the charged current (control) samples are calculated from the scaling model of reference 7. The neutral current data lie systematically below the charged-current data, reflecting a coupling constant smaller than the charged-current coupling by about a factor of 3. The directly observed partial ratios of neutral to charged current events obtained by integrating the data of Figure 3 are $R_\nu^p = 0.28 \pm .03$ and $R_{\bar{\nu}}^p = 0.35 \pm .11$ for $E_h^m > 12$ GeV.

These ratios only include data for $E_h \geq 12$ GeV and the extrapolation to zero hadron energy to yield total cross-section ratios will be different if the shapes of the hadron distributions for NC and CC events are different[10]. It should be emphasized, however, that the above ratios as well as the data of Figure 3 are completely independent of assumptions regarding the neutral current coupling. Without extrapolating, we can note that to the extent the measured ratios are different, the neutral current coupling is not of the pure V-A form of the charged current. The coupling is apparently not far from this form and a more complete analysis, presented in the following paper[9], is needed to determine the actual coupling.

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8. The resolution function used was of a Gaussian form $dR(E_h, E_h^m) = 1/\sqrt{2\pi\sigma^2}\, \exp\left[-(E_h - E_h^m)^2 / 2\sigma^2\right] dE_h^m$, and

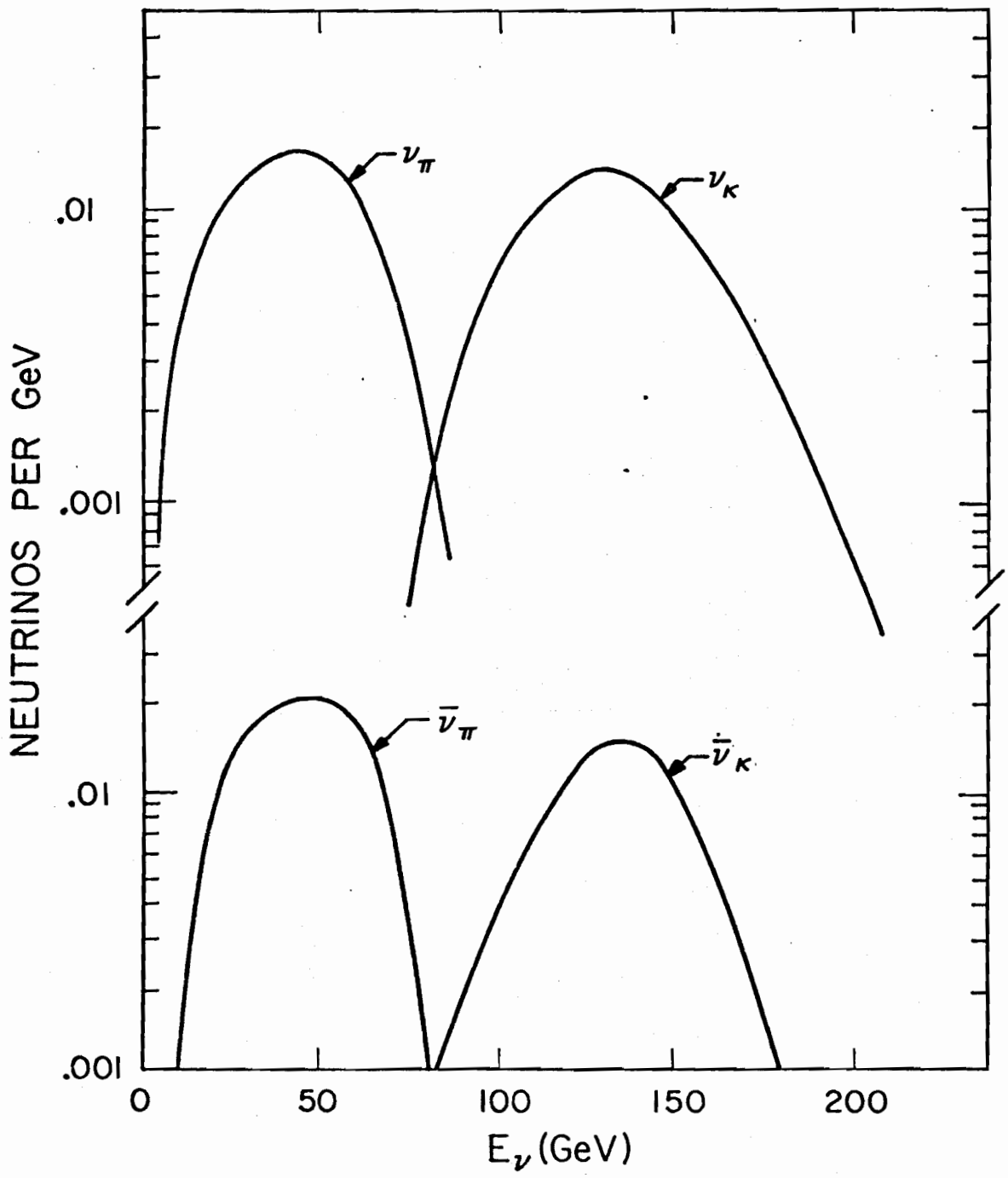
   $\sigma = 1.1\sqrt{E_h}$ (energy units are GeV).
9. F. Merritt et al., CALT 68-601 Preprint, "Determination of the V,A Structure of the Neutral Current Coupling",(following paper).
10. These partial ratios are independent of both the relative $\nu - \bar{\nu}$ normalization constraints and of any assumptions about the NC coupling. When the normalization constraint is included in specific models of the neutral current interaction (see reference 9), these ratios may change within the quoted errors.

Figure Captions

Figure 1: Calculated flux vs. energy incident onto the fiducial volume from the narrow band neutrino and antineutrino beams. Included are neutrinos from decays of pions (ν_π) and kaons (ν_K) in the decay pipe. Each spectrum (e.g. ν_π) has been normalized to unit integral.

Figure 2: Calculated efficiency for recognizing charged-current events induced by 60 GeV neutrinos. (a) All events with muon penetration greater than 1.6m steel. (b) Events after correcting for losses measured by azimuthal rotation of recognized events (see text). The dashed line indicates the effect of the 12 GeV trigger requirement.

Figure 3: The neutral current and charged current distribution in measured hadron energy using the model-independent techniques of azimuthal extrapolation for part of the charged current subtraction and y-intercepts for normalization. For comparison, the scaling model curves for $\alpha = 0.17$ for the charged currents (ref. 7), and $P = 0.38$ for the neutral currents (ref. 9) are shown.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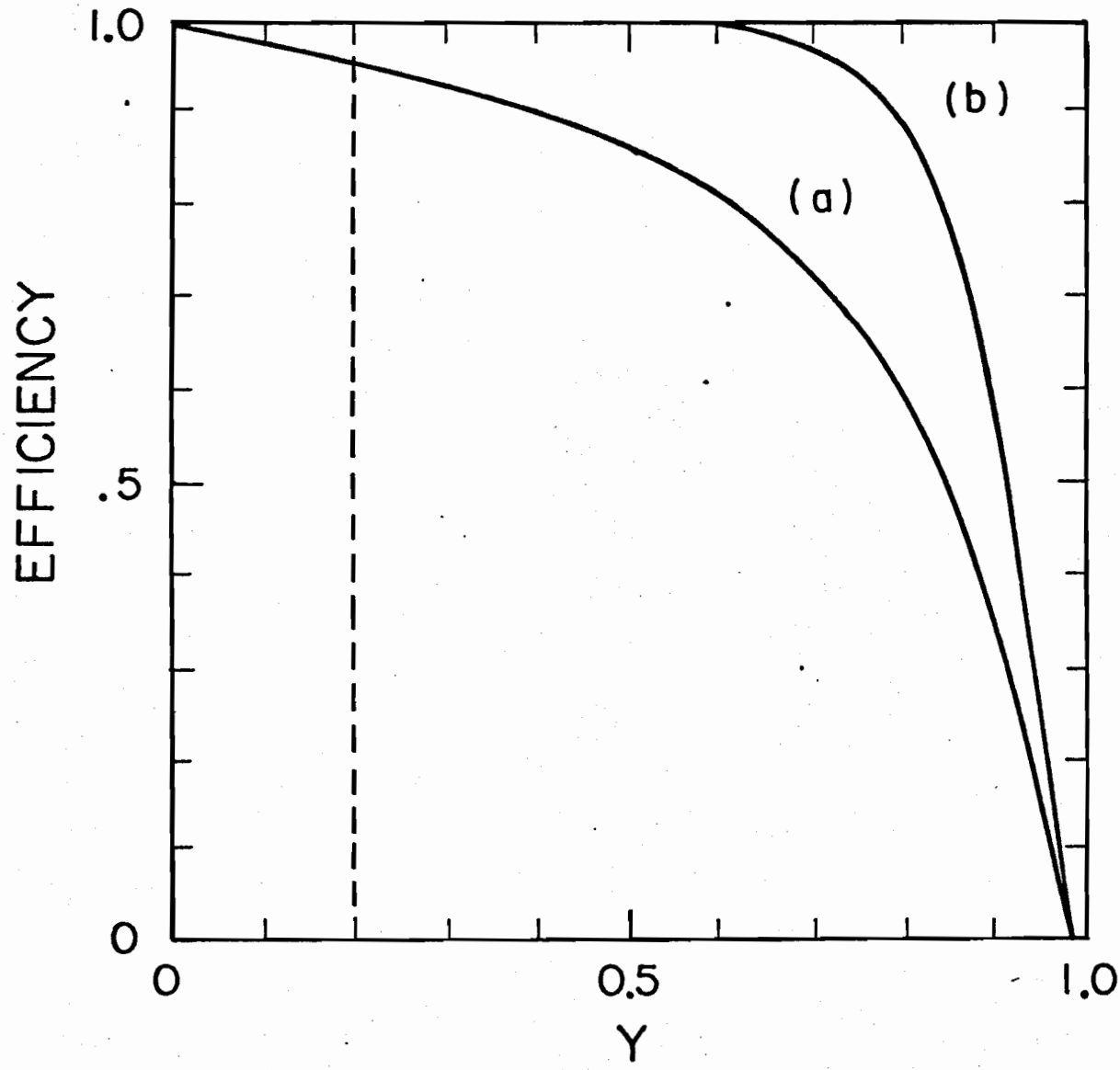
E_ν (GeV)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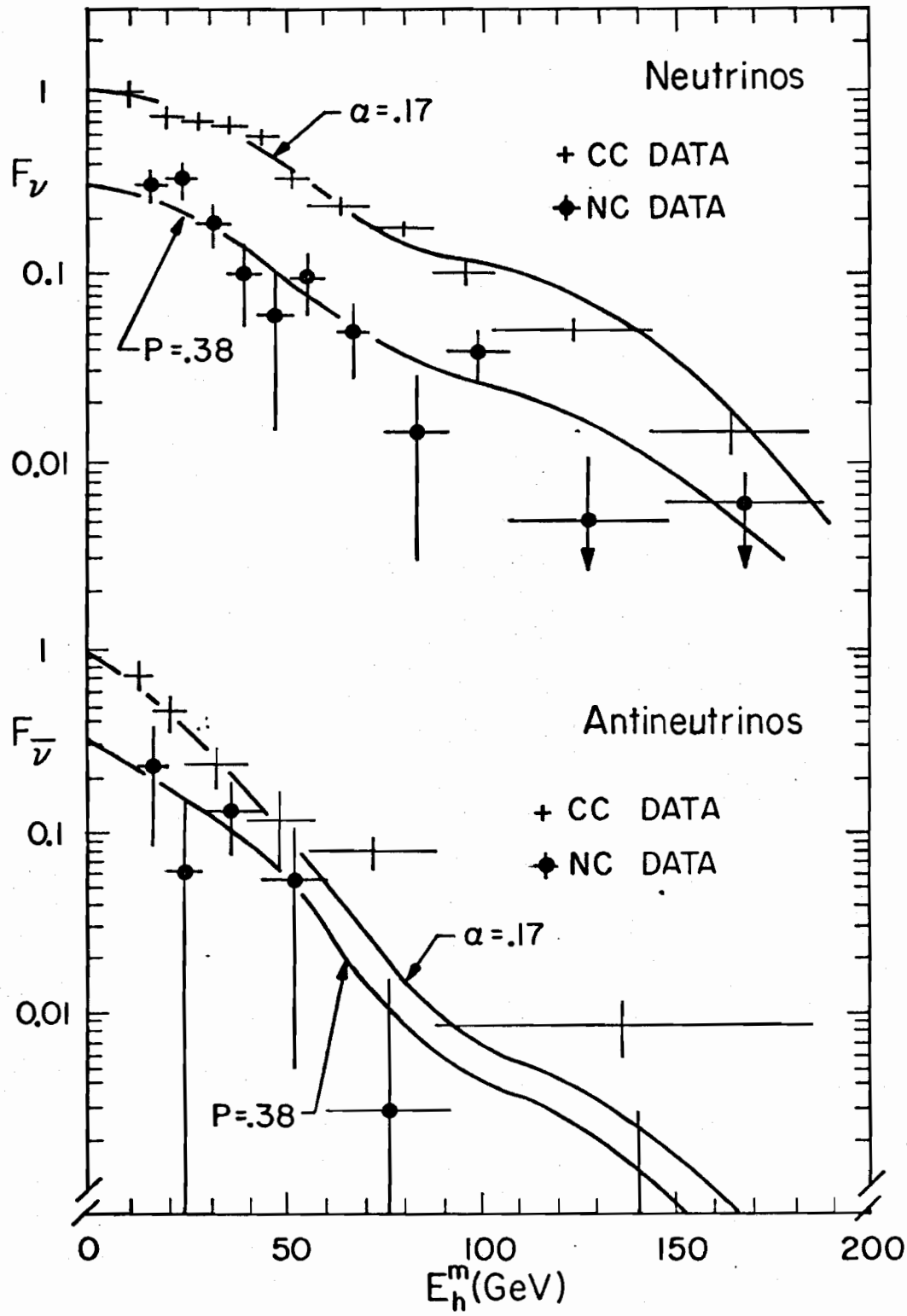
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E_h^m(GeV)