INVESTIGATIONS OF THE STRUCTURE OF THE NEUTRAL CURRENT COUPLING IN INCLUSIVE NEUTRINO INTERACTIONS*

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Abstract

Preliminary results from a neutral current experiment performed in the Fermilab narrow band neutrino beam are presented. The hadron energy distributions obtained from high-energy neutral current interactions in both neutrino and antineutrino beams are presented, and are used to infer constraints on the possible kinds of neutral current coupling. Strongly dominant scalar and pseudoscalar couplings are not consistent with the distributions observed, nor is a dominant V+A coupling. Very preliminary studies show no inconsistency with some combination of V+A and V-A couplings.

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Deep inelastic neutrino interactions with no final state muon were observed by the Caltech-Fermilab group in an experiment carried out in February 1974.[1] The major conclusions of that experiment were that ν_μ events in which no final state muon is produced occur at a level consistent with previous observations,[2] and that for such events unobserved energy is transported out of the target.

The most plausible explanation for these events is that they are neutral-current (NC) neutrino interactions $\nu\ (\bar{\nu}) + N \rightarrow \nu\ (\bar{\nu}) +$ hadrons, which couple through a neutral boson field as represented in figure 1(b). If this basic picture is correct, then NC events are similar in structure to charged current (CC) interactions (see figure 1(a)), and are expected to show similar scaling behavior in the deep inelastic region.[3]

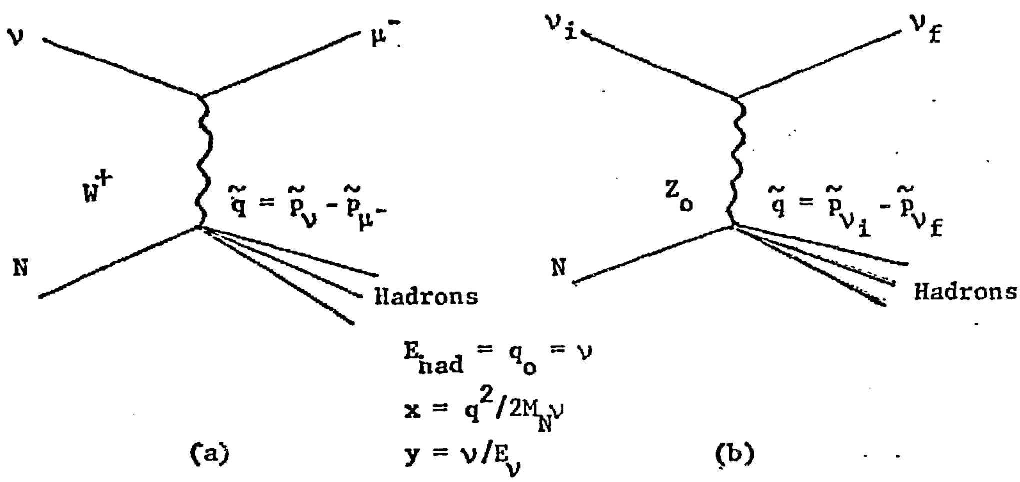
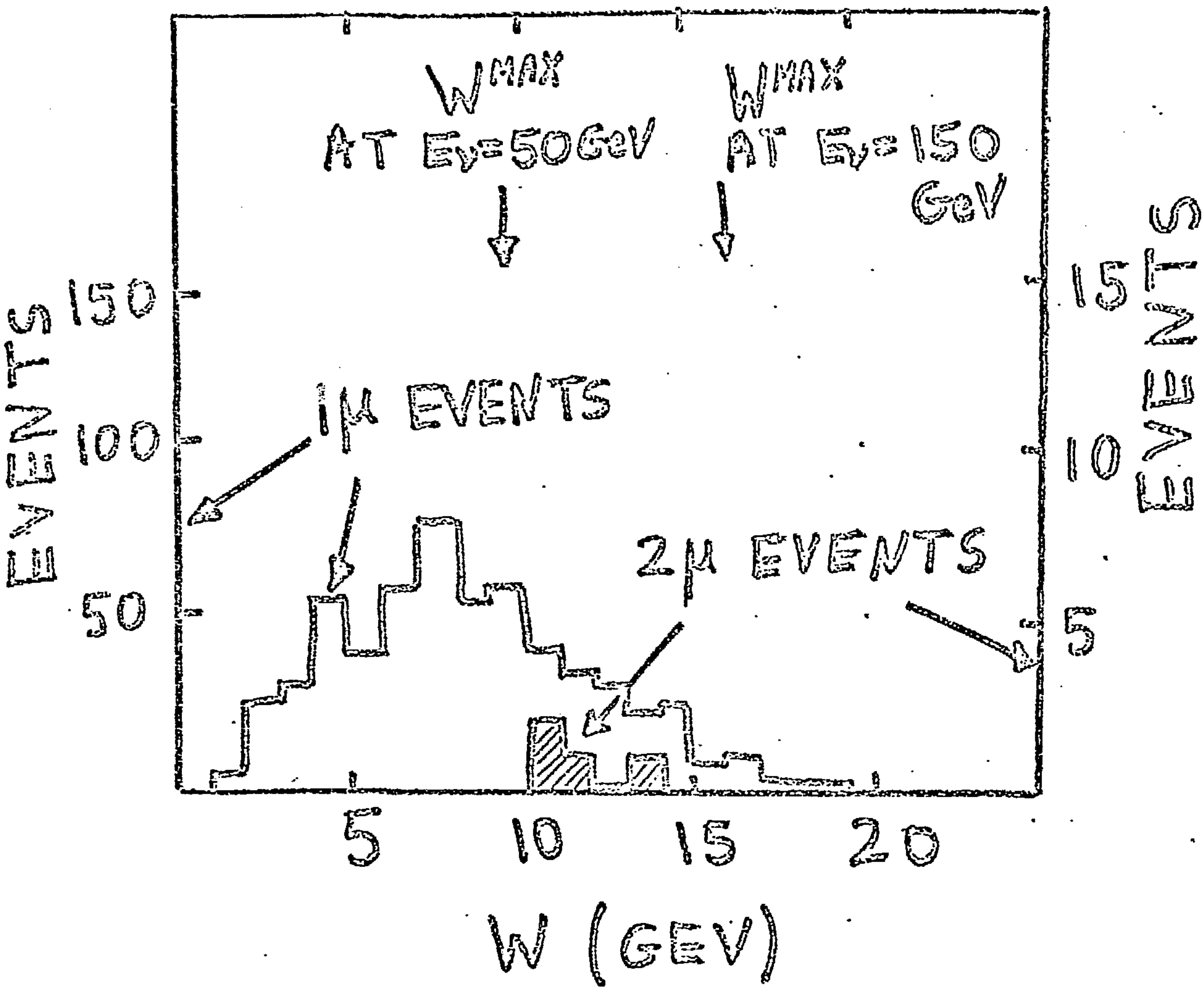


Figure 1

However, even within this framework, there could be major differences between the structure of NC and CC interactions. The NC coupling constant may be different from that of the CC interactions, and the Lorentz structure

Fig. 7



W^MAX AT Eγ=50GeV
W^MAX AT Eγ=150 GeV
EVENTS
150
100
50
1μ EVENTS
2μ EVENTS
EVENTS
15
10
5
5
10
15
20
W (GEV)

of the coupling may also be different. Whereas CC events occur through a V-A coupling, NC events could occur through V+A, or through a combination of V+A and V-A (as expected from the Weinberg model[4]). More generally, NC events could also occur via non-helicity-conserving couplings[5] such as scalar(S), pseudoscalar(P), and tensor(T). There has been little experimental evidence to determine the nature of the neutral current coupling and more experimental information is clearly needed.[6]

The different kinds of coupling would be reflected in the differential cross-section $d\sigma/dy$, where $y = E_{had}/E_\nu$ is the fraction of the incident neutrino energy transferred to the target nucleon. The helicity-conserving couplings V and A will produce a distribution with flat and $(1-y)^2$ components while a pure S or P coupling will produce a distribution that rises as y^2.[7]

Although y cannot be directly measured in NC events, these different y-distributions will be strongly reflected in the measured hadron energy (E_{had}) distributions for data obtained in a dichromatic neutrino beam. This had motivated us to carry out a second experiment, performed in September 1974, to measure the E_{had} distributions of neutral current events and so to obtain constraints on the possible kinds of NC couplings. The analysis is still in an early stage, and only the initial results will be presented here.

The experiment used the Fermilab narrow band beam with a 170 GeV sign-selected π and K beam to produce neutrinos in two energy bands centered at 50 and 150 GeV. Data was taken with both a neutrino and an antineutrino beam. A wide-band background component, coming from decays occurring before the beam was momentum-selected, was separately measured and subtracted from the data.

The neutrino interactions were observed in a target-calorimeter containing 140 tons of steel, 50 feet long and 5' × 5' in transverse dimensions. A liquid scintillation counter was located after every 10 cm of steel (= 1 collision length) and a spark chamber followed every second counter. The counters measured the energy E_{had} of the hadron shower and the range of the most penetrating particle produced in the interaction. The spark chambers measured the transverse coordinates of the interaction vertex and, for CC events, tracked the final state muon. The apparatus was triggered by a measured energy deposition of ≥ 9 GeV in coincidence with a charged-particle penetration of ≥ 2 collision lengths downstream of the interaction (the penetration requirement in the trigger was reduced somewhat from the preceding run in order to avoid bias against very short-range NC events).

To eliminate backgrounds (primarily from cosmic rays and accidental triggers) and to avoid any biases due to trigger inefficiency or uncertain event identification, all events used in the analysis were required to satisfy three conditions: 1) the measured energy deposition was ≥ 12 GeV; 2) the two spark chambers and two counters downstream of the vertex must show the passage of charged particles; and 3) the interaction must occur within a fiducial volume 5" from the sides of the apparatus, 112" from the downstream end, and 16" from the upstream end. This gives us a data sample which we believe to be composed almost entirely of neutrino interactions (both NC and CC). Backgrounds due to cosmic rays, neutrons, and electron neutrinos are minor and are discussed in reference 1.

Neutral currents are distinguished from charged currents by the penetration P (measured by the counters) of the most penetrating charged particle produced in the interaction. For CC events, this is generally the number of counters traversed by the muon before it leaves the apparatus through the sides or downstream end. For NC events, however, the final state neutrino gives no signal so the penetration is just the range of the hadron shower, usually < 14 counters. Figure 2 shows the penetration distribution of all neutrino events with $E_h > 12$ GeV. The peak in the low P region is the NC signal, and the smooth curve is the distribution expected from CC events alone (normalized to all events with $P > 20$).

As discussed previously, the Lorentz structure of the NC interaction is reflected in the hadron energy distribution of NC events. To extract this distribution, the data was divided into two penetration regions, $P \leq 14$ counters and $P > 14$ counters. The high-P region (figure 3(a)) contains most of the CC events, while the low-P region (figure 3(b)) contains essentially all the NC events plus CC events with wide-angle muons. The smooth curves are the calculated distributions expected from CC events. The calculation includes experimental resolutions and assumes scaling, a V-A coupling, the SLAC $F_2^{ed}(x)$ structure function, and spin 1/2 partons with no antipartons in the nucleon. These assumptions are consistent with previous fits to CC data[8] and reasonable deviations from them do not sensitively affect the extrapolation from high-P to low-P.

Subtracting the calculated CC background curve from the data in figure 3(b) gives the NC hadron energy distribution for neutrinos shown in figure 3(c). The three curves shown are calculated for $d\sigma/dy$ = flat, $(1-y)^2$, and y^2. All three curves are normalized to the data above E_{had} = 12 GeV. The flat y distribution looks most like the data .

The types of coupling can more easily be distinguished when correlations in magnitude, as well as shape, of the neutrino and antineutrino NC signals are considered. If NC events couple through the diagram of figure (1), then the assumptions of scaling and hermiticity of the neutral current imply a relationship between the shapes of the y-distributions of ν and $\bar{\nu}$, and also between the relative number of ν and $\bar{\nu}$ NC events:

$$\frac{dN^{\nu}}{dy} = F^{\nu}[\alpha + \beta(1-y)^2 + \gamma y^2] \quad - \gamma y^2$$

$$\frac{dN^{\bar{\nu}}}{dy} = F^{\bar{\nu}}[\beta + \alpha(1-y)^2 + \gamma y^2] \quad - \gamma y^2$$

where F_{ν} ($F_{\bar{\nu}}$) is a flux factor depending on the number of incident ν ($\bar{\nu}$). When a particular model is fitted to the NC E_{had} distribution of neutrinos, this relation predicts both the size and the shape of the corresponding antineutrino distribution; the ratio of the flux factors F_{ν} and $F_{\bar{\nu}}$ is obtained from the CC events recorded during the run, together with the previously measured ratio of CC total cross-sections.[8]

Each of the three curves fitted to the E_{had} distribution of ν NC events in figure 3(c) therefore predicts a corresponding curve for antineutrinos. Dominant V-A, V+A, and S or P couplings correspond to dominant α, β, and γ, respectively. The three predicted curves are compared to the E_{had} distributions of $\bar{\nu}$ NC events in figure 4. A dominant γ distribution is clearly inconsistent with the data, as is a dominant β distribution. A pure α fit is also ruled out, but a combination of α and β, with somewhat more α than β, is consistent with the data.

The calculation of the total cross-section ratios $R_{\nu,\bar{\nu}} = \sigma_{NC}^{\nu,\bar{\nu}}/\sigma_{CC}^{\nu,\bar{\nu}}$ depends strongly on the shape assumed for the E_{had} distributions, since the fitted curves must be extrapolated to $E_{had} = 0$. In order to show the sensitivity to the shape assumed for $d\sigma/dy$, we list in the table below the "raw" unextrapolated ratios of NC/CC events, together with the corrected (extrapolated) ratios obtained by assuming each of the three shapes considered.

	"Raw"	Extrapolated		
	($E_{had} \geq 12$)	Pure α	Pure β	Pure γ
R_ν	.21	.23	.37	.18
$R_{\bar{\nu}}$	.43	.50	.31	.24
$R_{\bar{\nu}}$ (predicted)		.23	3.33	.54

The top row uses the α, β, and γ distributions normalized to the ν NC data to obtain values of R_ν; the bottom two rows compare the analagous values of $R_{\bar{\nu}}$ to the predicted values obtained from R_ν (corresponding to the curves in fugure 4). The predicted value is low if pure α is assumed and very high if pure β is assumed; if the coupling is in fact a combination of V-A and V+A, we expect the true values of $R_{\nu,\bar{\nu}}$ to lie somewhere between the limits of pure α and pure β given in the table (and probably closer to α than to β). This range of values is in general agreement with the Gargamelle ratios of $R_\nu = .22 \pm .03$ and $R_{\bar{\nu}} = .43 \pm .12$,[9] and is also consistent with the predictions of the Weinberg model.

There is nothing to prevent one from calculating the mixture of α, β, and γ that gives a best fit to both ν and $\bar{\nu}$ data. However, there are several sources of possible error that must be studied before such a fit is very meaningful. For example, we have assumed in the calculation that CC events couple through pure V-A with no antiquark component in the nucleon. If this assumption is relaxed, both the subtraction of CC events in the low-penetration region and the extrapolation of the E_{had} distributions to low hadron energy are altered, and the $R_{\bar{\nu}}$ ratios can increase by as much as 20% (the effect on R_ν is much smaller). The CC interactions must be studied in greater detail, then, to determine how much antiquark component can be tolerated and to check the accuracy of the extrapolations in E_{had}. There are also some possible systematic effects in the data itself; for example, some of the very high energy NC hadron showers penetrate through more than 14 counters and contribute to the long-penetration region rather than to the short-penetration region.

Another effect that must be investigated is the possible energy dependence of the NC total cross-section. This analysis has assumed a linearly rising cross-section for neutral currents, and the agreement between the $R_{\nu,\bar{\nu}}$ range indicated above and the Gargamelle measurement provides some support for this assumption. To make an independent measurement of the energy dependence we have varied the incident neutrino spectrum by steering the hadron beam away from the center of the apparatus by 1 - 2 mrad. Since the neutrinos from π-decay (centered at ~50 GeV) are more collimated than those from K-decay (centered at ~150 GeV), the effect is to decrease the size of the incident 50 GeV band relative to the 150 GeV band. By comparing the NC/CC ratios at different steering angles and by studying deviations in the E_{had} distributions of NC events as a function of steering angle, we hope to obtain a measure of the E_ν dependence and perhaps to better measure the shape of the y distributions.

The analysis is still, then, in a fairly early state, and several corrections and tests need to be made. However, a dominant γ distribution ($d\sigma/dy \propto y^2$) as expected from strongly dominant P and S couplings is clearly inconsistent with the data, and a dominant β distribution (expected from V+A coupling) is even more inconsistent. These conclusions are insensitive to further corrections and refinements in the analysis.

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B. Aubert, et.al., Phys. Rev. Lett. 32, 1454 and 1457 (1974);
S. J. Barish, et.al., Phys. Rev. Lett. 33, 448 (1974).

3. If the mass of the Z_o is small, propagator effects will introduce an energy-dependent reduction in $d\sigma/dy$ in the large y region and the NC total cross-section will deviate from a linear increase with E_ν.

4. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967) and 27, 1683 (1972).
A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964).

5. B. Kayser, et.al., Phys. Lett. 52B, 385 (1974); R. L. Kingsley, F. Wilczek, A. Zee, Phys. Rev. D10, 2216 (1974).

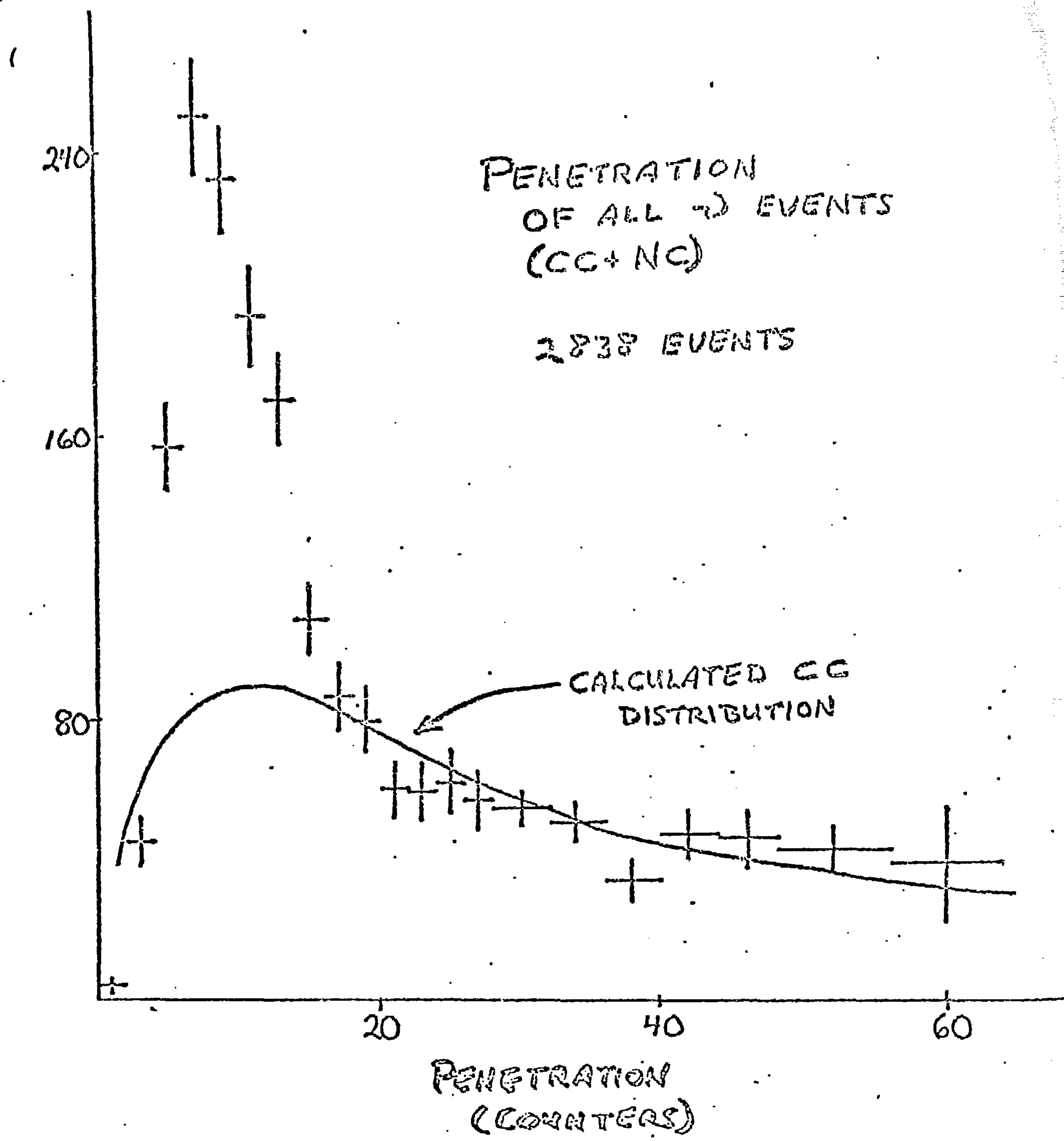
6. In particular, data on single pion production by neutral currents (P. Schreiner, XVII Int'l. Conf. on High Energy Physics, London 1974, IV-123) has resulted in speculations that neutral currents may have S, P, or T couplings (S. L. Adler, Phys. Rev. Lett. 33, 1511 (1974)). Note that more recent results of that experiment have been presented in this conference.

7. In general, it is always possible to find some combination of P, S, and T that will mimic both the ν and $\bar{\nu}$ y-distributions of any given combination of V-A and V+A (see reference 5). It is impossible in principle to distinguish the two possibilities in a deep-inelastic neutrino experiment. Our emphasis here is to determine whether any large deviations from the V and A structure are apparent through deviations from the expected y behavior.

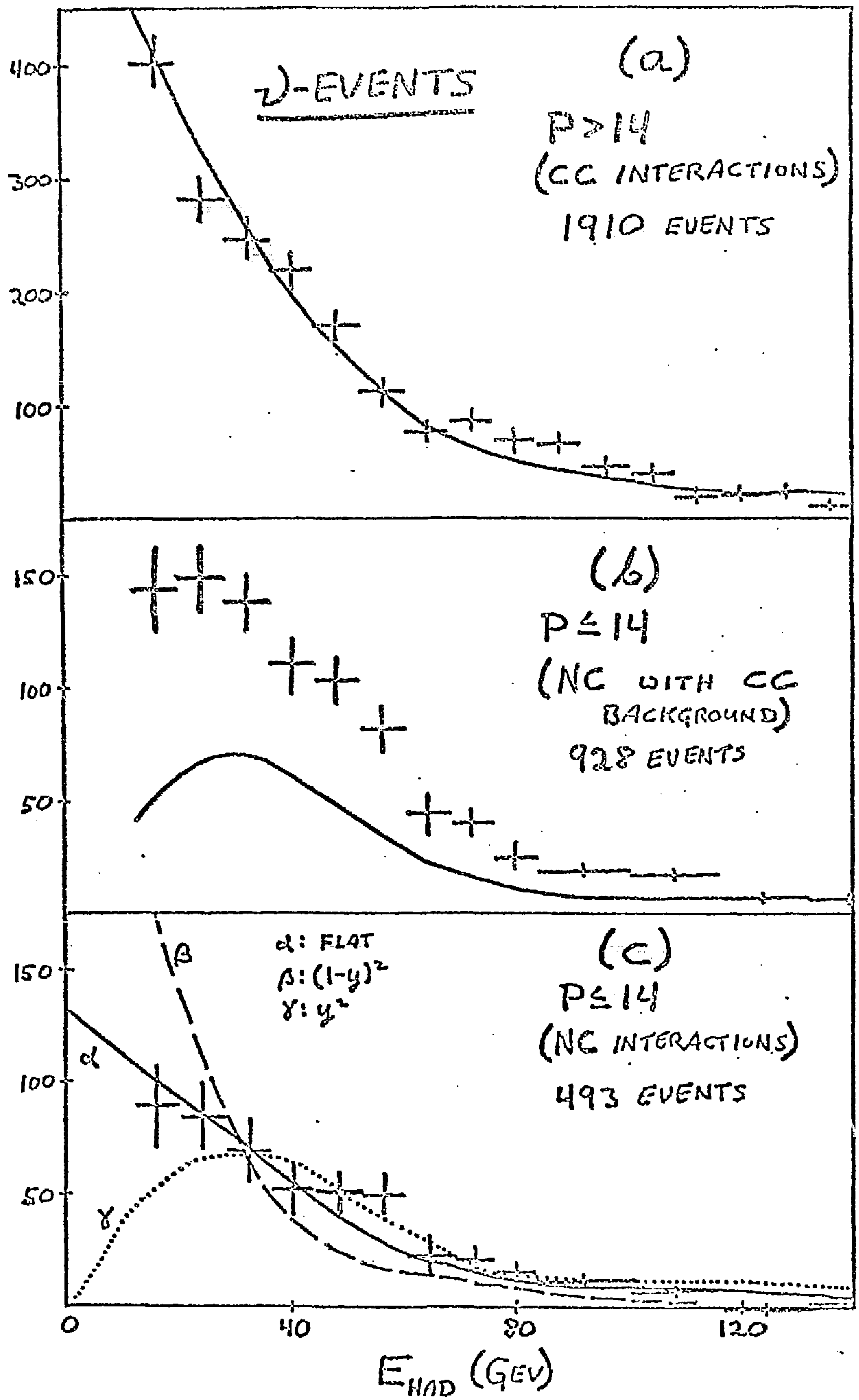
8. F. Sciulli, XVII Int'l. Conf. on High Energy Physics, London, 1974, IV-105.

9. A. Pullia, XVII Int'l. Conf. on High Energy Physics, London, 1974, IV-114.

FIGURE (2)

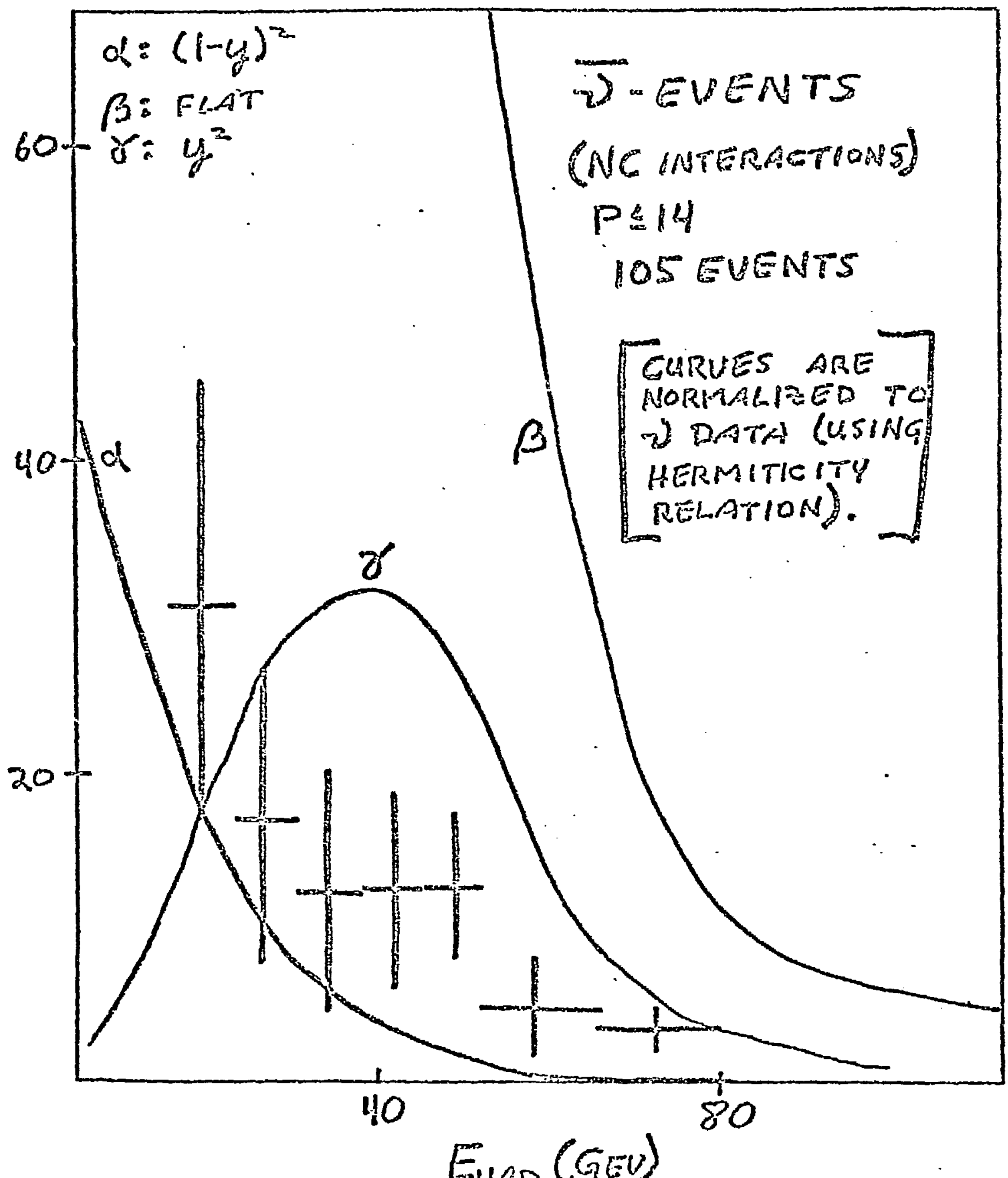


240
160
80
20
40
60
PENETRATION OF ALL ν EVENTS (CC+NC)
2838 EVENTS
CALCULATED CC DISTRIBUTION
PENETRATION (COUNTERS)



400
300
200
100
(a)
ν-EVENTS
P>14
(CC INTERACTIONS)
1910 EVENTS
150
100
50
(b)
P≤14
(NC WITH CC BACKGROUND)
928 EVENTS
150
100
50
β
α: FLAT
β: (1-y)²
γ: y²
(c)
P≤14
(NC INTERACTIONS)
493 EVENTS
α
γ
0
40
80
120
E_HAD (GEV)

FIGURE (4)



α: $(1-y)^2$
β: FLAT
γ: y^2
$\bar{\nu}$-EVENTS
(NC INTERACTIONS)
P≤14
105 EVENTS
[CURVES ARE NORMALIZED TO $\bar{\nu}$ DATA (USING HERMITICITY RELATION).]
60
40
20
α
β
γ
40
80
E_{HAD} (GEV)