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Publication Date
1975-06-01

Submitted to Nuclear Physics B

LBL-3862
Preprint c.1

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June 5, 1975

Prepared for the U.S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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HAS CHARM BEEN SEEN IN NEUTRINO EXPERIMENTS?*

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Abstract

In view of the possible new threshold in neutrino-hadron deep inelastic scattering recently seen at Fermilab, we examine the possibility that the new produced particles are the charmed particles predicted by Glashow, Iliopoulos, and Maiani. We find qualitative agreement but indications of quantitative disagreement between theory and experiment. The disagreement is only at the one standard deviation level so that a conclusive test of the charm model must await better statistics and further clarification of possible systematic errors in the data.

1. Introduction

Recent neutrino experiments at FNAL[1,2] have begun to give indications of a new particle threshold at relatively high energy. This threshold manifests itself most clearly as an anomalous contribution to deep inelastic antineutrino scattering at high y, i.e., high energy transfer between the leptonic and hadronic systems[3], which is present above 30 GeV and absent below. Alternatively, if the cross

* This work was supported by the U. S. Energy Research and Development Administration.

sections are plotted versus the mass of the final state hadronic system, $\sqrt{W^2}$, there is a small excess over the theoretical prediction beginning at about $W \simeq 4$-5 GeV in the antineutrino data[4]. If we are willing to accept these data as evidence for the existence of new high mass particles, then we should naturally wonder about their identity. One attractive possibility is that they are the charmed particles already predicted by Bjorken and Glashow[5], and Glashow, Iliopoulos, and Maiani[6] (GIM).

The GIM model, of course, makes predictions about the properties of the charmed particles which can, in principle, be tested. In what follows, we will discuss how to best test the model; we will see that the model fits the data qualitatively but tends to disagree with the data quantitatively.

The processes we are concerned with are of the type

$$\nu(\bar{\nu}) + N \rightarrow \mu^-(\mu^+) + X \ ,$$

where N is some nucleonic target with roughly equal numbers of neutrons and protons and X is some final hadronic state. We are primarily interested in the subset of these events in which a charmed particle is contained in X. If this subset is not the empty set then we can search for charm in two ways: (1) we can look more closely at the decay of the charmed particle, or (2) we can examine the mechanism by which the charmed particle was produced. The decay of a charmed particle produced in a neutrino experiment has certain features which are relatively simple to distinguish experimentally. If the charmed particle decays semileptonically so that the final state has two muons, then the muons must necessarily have opposite charges. Several such dimuon events have already been seen[7]. If the particle decays hadronically, then the model predicts that a large fraction of the time the event will obey the relation $\Delta S = -\Delta Q$. There is at present one candidate for this type of event: $\nu p \to \mu^- \Delta \pi^+ \pi^+ \pi^+ \pi^-$ [8]. These types of experiments give qualitative support to the charm hypothesis; however, it is difficult to make any quantitative test of the model this way. Not only do the rates for these processes depend on the incoming neutrino fluxes, they also depend on branching ratios which are probably beyond our ability to calculate.

Charm production, on the other hand, is a theoretically well-defined process. Within the framework of the quark parton model[9], the contributions of charm production to the differential cross sections are completely determined in terms of the various quark distribution functions. These distributions, in turn, are determined by the cross sections below charm threshold. The previously mentioned problem of the poorly defined neutrino flux can be circumvented by measuring not the absolute normalization of the differential cross sections, but only their shapes.

2. Cross Sections and Distribution Functions

The starting point for any analysis of this type is the specific form of the differential cross sections. When the GIM model is joined together with the quark parton model the following predictions emerge. Below charm threshold the cross sections (in the standard units of G^2ME/π) are

$$\frac{d^2\sigma_b}{dxdy} = 2\{xn(x)\cos^2\theta_c + x\bar{p}(x)(1-y)^2 + x\lambda(x)\sin^2\theta_c\}$$

$$\frac{d^2\sigma_b}{dxdy} = 2\{xp(x)(1-y)^2 + x\bar{n}(x)\cos^2\theta_c + x\bar{\lambda}(x)\sin^2\theta_c\} \quad . \tag{1}$$

Above charm threshold there are additional pieces

$$\frac{d^2\sigma_a}{dxdy} = 2\{xn(x)\sin^2\theta_c + x\lambda(x)\cos^2\theta_c\}\theta(sy(1-x) - W_o^2)$$

$$\frac{d^2\bar{\sigma}_a}{dxdy} = 2\{x\bar{n}(x)\sin^2\theta_c + x\bar{\lambda}(x)\cos^2\theta_c\}\theta(sy(1-x) - W_o^2) \quad . \tag{1'}$$

Here $\bar{\sigma}$ is the antineutrino cross section and σ is the neutrino cross section; x and y are the usual scaling variables; and $n(x)$, $p(x)$, etc. are the x distributions of the various quark types in the target nucleus [3]. W_o corresponds to an effective charm threshold. W_o may differ slightly from the actual threshold value since the θ-function threshold behavior we have assumed may not be so good right near the threshold. In any case, we can treat W_o as a curve fitting parameter, with the understanding that it should not differ dramatically from about 4 or 5 GeV. Also we should point out that we have assumed that there are no significant amounts of charmed quarks or antiquarks in the nucleon's "sea". This assumption is motivated by the theoretical prejudice that charmed quarks are effectively much more massive than ordinary quarks, and also, if we interpret the $\psi(3095)$ and its neighbors as $\bar{c}c$ states, by the small coupling of the ψ's to ordinary hadronic matter.

In any case, equations (1) and (1') demand that, in addition to W_o, we know six quark distributions. We can lower this number if we remember that we have assumed a target with equal numbers of protons and neutrons; then the cross sections per nucleon become

$$\frac{d^2\sigma_b}{dxdy} = 2\{xq(x)\cos^2\theta_c + x\bar{q}(x)(1-y)^2 + xs(x)\sin^2\theta_c\}$$

$$\frac{d^2\bar{\sigma}_b}{dxdy} = 2\{xq(x)(1-y)^2 + x\bar{q}(x)\cos^2\theta_c + xs(x)\sin^2\theta_c\} \qquad (2)$$

$$\frac{d^2\sigma_a}{dxdy} = 2\{xq(x)\sin^2\theta_c + xs(x)\cos^2\theta_c\}\theta\left(sy(1-x) - W_o^2\right)$$

$$\frac{d^2\bar{\sigma}_a}{dxdy} = 2\{x\bar{q}(x)\sin^2\theta_c + xs(x)\cos^2\theta_c\}\theta\left(sy(1-x) - W_o^2\right) \qquad (2')$$

where

$$q(x) = \tfrac{1}{2}\left(p(x) + n(x)\right)$$

$$\bar{q}(x) = \tfrac{1}{2}\left(\bar{p}(x) + \bar{n}(x)\right) \qquad (3)$$

$$s(x) = \lambda(x) = \bar{\lambda}(x) \ .$$

In principle $q(x)$, $\bar{q}(x)$, and $s(x)$ can be determined by three experiments--neutrino and antineutrino experiments below charm threshold, and deep inelastic electron scattering from a deuterium target. For instance, if we integrate equations (2) over y and then take their difference we find

$$\frac{d\sigma_b}{dx} - \frac{d\bar{\sigma}_b}{dx} = 2(\cos^2\theta_c - \tfrac{1}{3})x\left(q(x) - \bar{q}(x)\right)$$

which is proportional to the "valence" or "nonsea" part of the quark distribution. Similarly the sum of the two integrated cross sections is just

$$\frac{d\sigma_b}{ax} + \frac{d\bar{\sigma}_b}{dx} = 2(\cos^2\theta + \tfrac{1}{3})x\left(q(x) - \bar{q}(x)\right) + 4\sin^2\theta\, xs(x)$$

while for electroproduction

$$\tfrac{9}{5}F_2^{ed}(x) = 2\left(x\left(q(x) + \bar{q}(x)\right) + \tfrac{2}{5}x\, s(x)\right) \ .$$

If we neglect the Cabibbo angle for the moment[10] we have

$$\tfrac{3}{2}\left(\frac{d\sigma_b}{dx} - \frac{d\bar{\sigma}_b}{dx}\right) = 2x\left(q(x) - \bar{q}(x)\right) \qquad (4)$$

$$\tfrac{3}{4}\left(\frac{d\sigma_b}{dx} + \frac{d\bar{\sigma}_b}{dx}\right) = 2x\left(q(x) + \bar{q}(x)\right) \qquad (4')$$

$$\tfrac{9}{5}F_2^{ed}(x) = 2x\left(q(x) + \bar{q}(x) + \tfrac{2}{5}s(x)\right) \ . \qquad (4'')$$

Notice that at high x, where $\bar{q}$ and s are supposed to be negligible the three distributions are expected to be equal, while at low x the difference between the second and third distributions should give us the size of the strange quark distribution. The relevant data[11] are shown in fig. 1. The neutrino data is from CERN with energies below 10 GeV. The electron-deuterium data is from SLAC. As expected the distributions coincide for large x.

An adequate fit to the data is given by the following parametrization:

$$q(x) = q_s(x) + q_v(x)$$

$$q_v(x) = \tfrac{1}{2}\left(4.7(1-x)^3 + 3.1(1-x)^4 + 1.35x^{-\frac{1}{2}}(1-x)^5\right) \quad (5)$$

$$s(x) = \bar{q}(x) = q_s(x) = 0.16x^{-1}(1-x)^7 \ .$$

The functional form of these equations is similar to that suggested by Gunion[12)] and Farrar[13)] on theoretical grounds which we will not discuss here.

Substituting these distributions into equations (4) yields the curves drawn in fig. 1. The lower solid curve is the valence quark distribution (4). The upper solid curve is (4') and the dotted curve is (4"). We have used an SU(3) symmetric sea in our fit. The closeness of the data for (4') and (4") precludes making the strange quark density much larger, although the data would seem to admit making it much smaller, or even zero[14)]. (In view of this we should probably take the SU(3) symmetric case as an upper limit on the strange quark component. Thus, our subsequent results should really be taken as <u>upper</u> limits on the expected effects of charm production.)

3. The Effects of Charm Production

Armed with equations (2) and (5) we are now equipped for our original task, which was to predict the change in shape of the (x,y) distributions due to the production of charmed particles. At this point, however, it is wise to bear in mind the nature of the experiment. The FNAL data[2)] we are analyzing represent only about one thousand events. Therefore, we should average the data over one or

more variables to cope with the large statistical errors. There are two ways to do this: we can average over the neutrino energy and plot, say, $\frac{d\sigma}{dy}$ versus y; or we can average over some scaling variable and plot something like $\langle y \rangle$ versus E_ν. The first method has the disadvantage of depending on the incoming neutrino and antineutrino fluxes which as pointed out previously are subject to error. To avoid this problem we take the second approach.

Figure 2 shows the predictions for $\langle x \rangle$ versus E and $\langle y \rangle$ versus E for neutrino and antineutrino scattering. We have put the charm threshold at $W_o = 7$ GeV to conform to the actual data shown in fig. 4. Only for the antineutrino data are there appreciable changes as we cross threshold, the largest being a 13% change in $\langle y \rangle$ vs. E.

Notice that while $\langle y \rangle$ increases, $\langle x \rangle$ decreases. To enhance the charm effect we should use a variable which combines both effects. Such a variable is the one we call r:

$$r = \frac{W^2}{s} = y(1-x) \ .$$

r is large for large y and small x and is perhaps the most logical variable to use when looking for a threshold effect since it is a simple function of W^2. For the sake of completeness we also mention the variable v;

$$v = \frac{Q^2}{s} = xy \ ,$$

which has the advantage of depending only on the variables of the final muon and not on the hadron energy. Unfortunately it is a poor variable to use in our case since it is very insensitive to any threshold effect--if $\langle x \rangle$ increases, and $\langle y \rangle$ decreases, then $\langle xy \rangle$ tends to remain the same. The predictions for $\langle r \rangle$ and $\langle v \rangle$ versus E are shown in fig. 3. The antineutrino $\langle r \rangle$ changes by 17% while the changes in the $\langle v \rangle$ distributions are almost imperceptible.

We now confront theory with experiment. The FNAL data[1] are given as the graphs of $\langle y \rangle$ and $\langle v \rangle$ versus E shown in fig. 4. This is the raw data. The low E fall-off of the neutrino data is due to the limited angular acceptance of the detectors. The slight rise in the autineutrino $\langle y \rangle$ at low E is due to a cut which omits events with $Q^2 \leq 1$ and $W \leq 1.6$, i.e., low y. When the acceptance, cuts, etc. are folded into the theoretical cross sections, we arrive at the solid lines in fig. 4. The dotted lines show what we would expect without charm (an undrawn dotted line indicates that it is nearly indistinguishable from the solid line). Again for the sake of completeness we show what the same analysis would give for $\langle r \rangle$ versus E in fig. 5. The graphs of fig. 4 show some very interesting features. While graphs (a) and (b) show good agreement between the theory and experiment, graphs (b) and (c) are in marked disagreement.

What can be the source of this disagreement? First, we look at graph (b). $\langle y \rangle$ is considerably higher than was expected. From a theoretical standpoint this might be due to a much larger density of strange quarks in the sea than anticipated. It is hard to see why these strange quarks are not seen in the lower energy data of fig. 1. Also, we cannot attribute the high $\langle y \rangle$ to charmed quarks in the sea since they always contribute to the cross sections with a $(1 - y)^2$ factor, i.e., they tend to contribute to low y events. Thus, (b) seems to contradict the charm hypothesis. (We should bear in mind, however, that it seems to violate charm by only one standard deviation.)

Equally disturbing is graph (c). The experimental $\langle v \rangle$ values are consistently below the theoretical prediction. It has been suggested[2] that this might be an effect due to the finite mass of the intermediate vector boson (IVB). This propagator effect would add a factor $(1 + \alpha v)^{-2}$ to all the cross sections (1), where $\alpha = 2ME/M_W^2$. However, to fit the data a comparatively light mass is required: $M_W \sim 15$ GeV. This mass is much lighter than that predicted by the usual gauge theories of weak and electromagnetic interactions. We should also bear in mind that the propagator necessary to improve agreement in (c) will only make the situation for (b) worse.

There is a way to solve both problems. If we assume that there is some systematic error such that the energy of the final muon is always underestimated, then v would be consistently underestimated and y would be overestimated. It remains, of course, an open experimental question whether such a systematic error exists or whether correcting this hypothetical problem could generate agreement between theory and experiment.

IV. Conclusions

There are two ways to resolve the discrepancies reported in this paper. The first is to take the discrepancies seriously and to assume that further experimentation will only corroborate the preliminary results. In that case there must be a breakdown in the theory. Either the GIM model is quantitatively wrong, or it is inappropriate to use the quark parton model to analyze these experiments, or the particular quark distributions we have used may be wrong. If either or both of the first two possibilities is the case then we are forced to make major revisions in our understanding of weak interactions involving hadrons. On the other hand, if the use of the quark parton model is justified then our parametrization of the quark distributions would seem to be on reasonably firm footing.

Another approach is to assume that the discrepancies are due to an experimental problem which will be resolved. In that case we merely restate that the best place to see charm is in the antineutrino $\langle y \rangle$ and/or $\langle r \rangle$ vs E curves. We expect charm to produce a deviation in these curves of order 15% or less so that the statistics would probably have to be improved significantly before we could distinguish between the theories with and without charm. A look at the error bars in fig. 4(b) indicates that at present they are at least as large as the effect we want to see. An improvement by at least a factor of three in the size of the errors would seem to be required before we could hope to begin to make a serious quantitative analysis.

We await further experiment to decide which of the above approaches is the correct one.

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FIGURE CAPTIONS

Fig. 1. Experimental data for the quark distribution functions defined by equations (4) of the text. The solid and dotted lines are our fit to the data using equations (5).

Fig. 2. Predictions for the curves $\langle x \rangle$ versus E (a) and $\langle y \rangle$ versus E (b) with incident neutrinos and antineutrinos. The small arrows show the position of the charm threshold.

Fig. 3. Predictions for the curves $\langle r \rangle$ versus E (a) and $\langle v \rangle$ versus E (b) with incident neutrinos and antineutrinos.

Fig. 4. Raw experimental data for $\langle y \rangle$ versus E and $\langle v \rangle$ versus E with incident neutrinos and antineutrionos. The solid lines show the expected shape of the curves in the charm model. The dotted lines are the expected curves without charm.

Fig. 5. Charm model predictions for the curves of $\langle r \rangle$ versus E for incident neutrinos and antineutrinos.

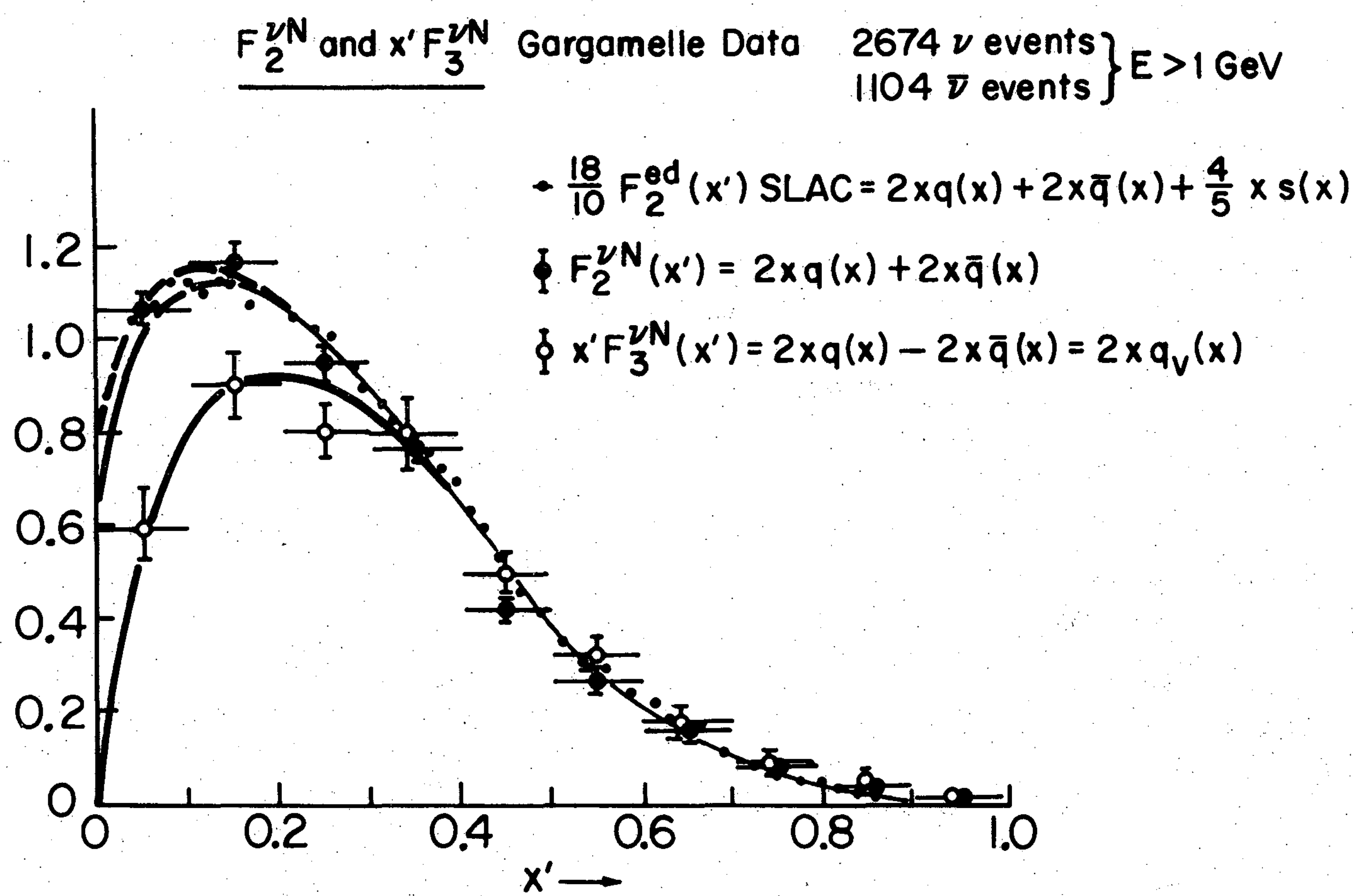

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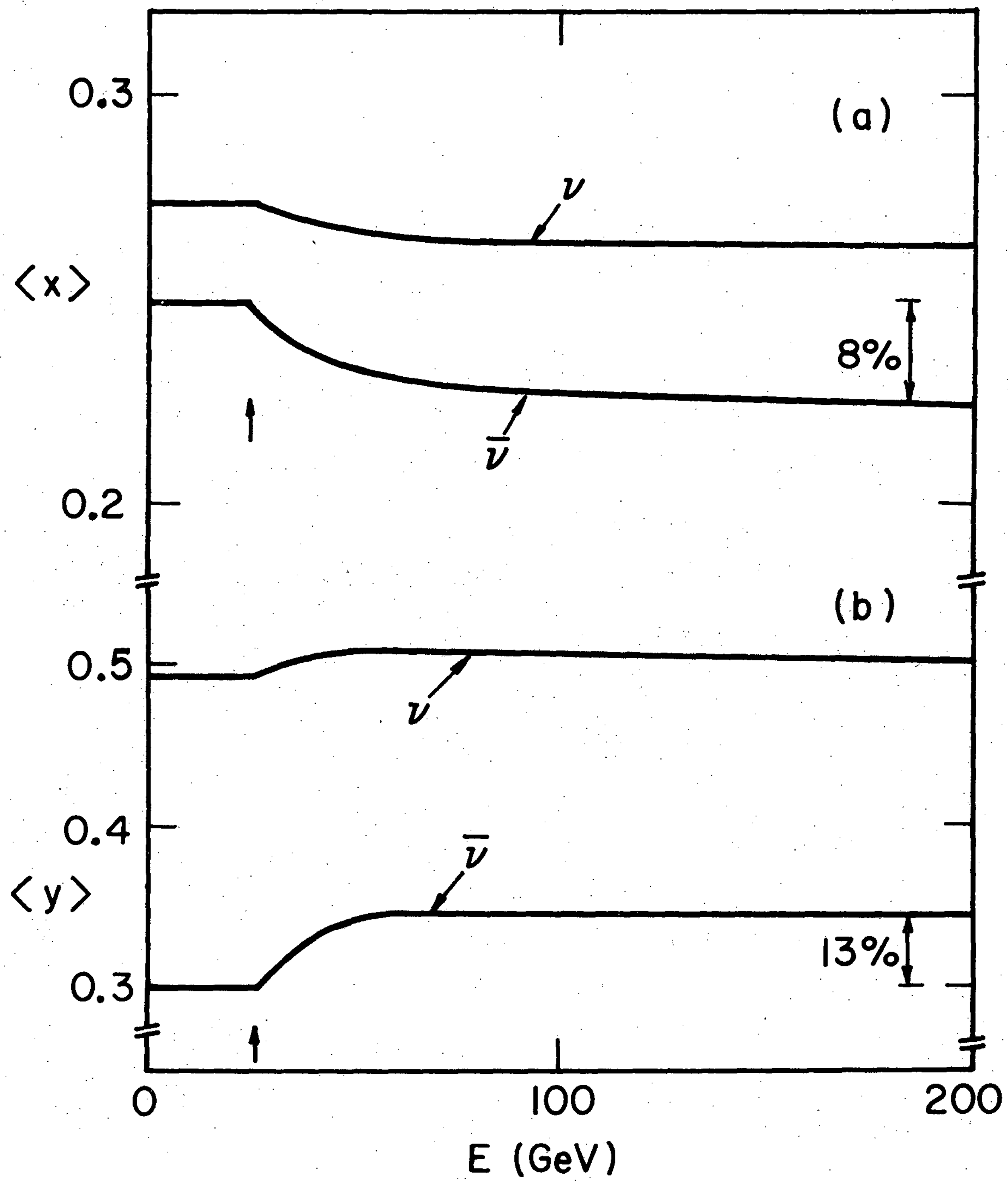
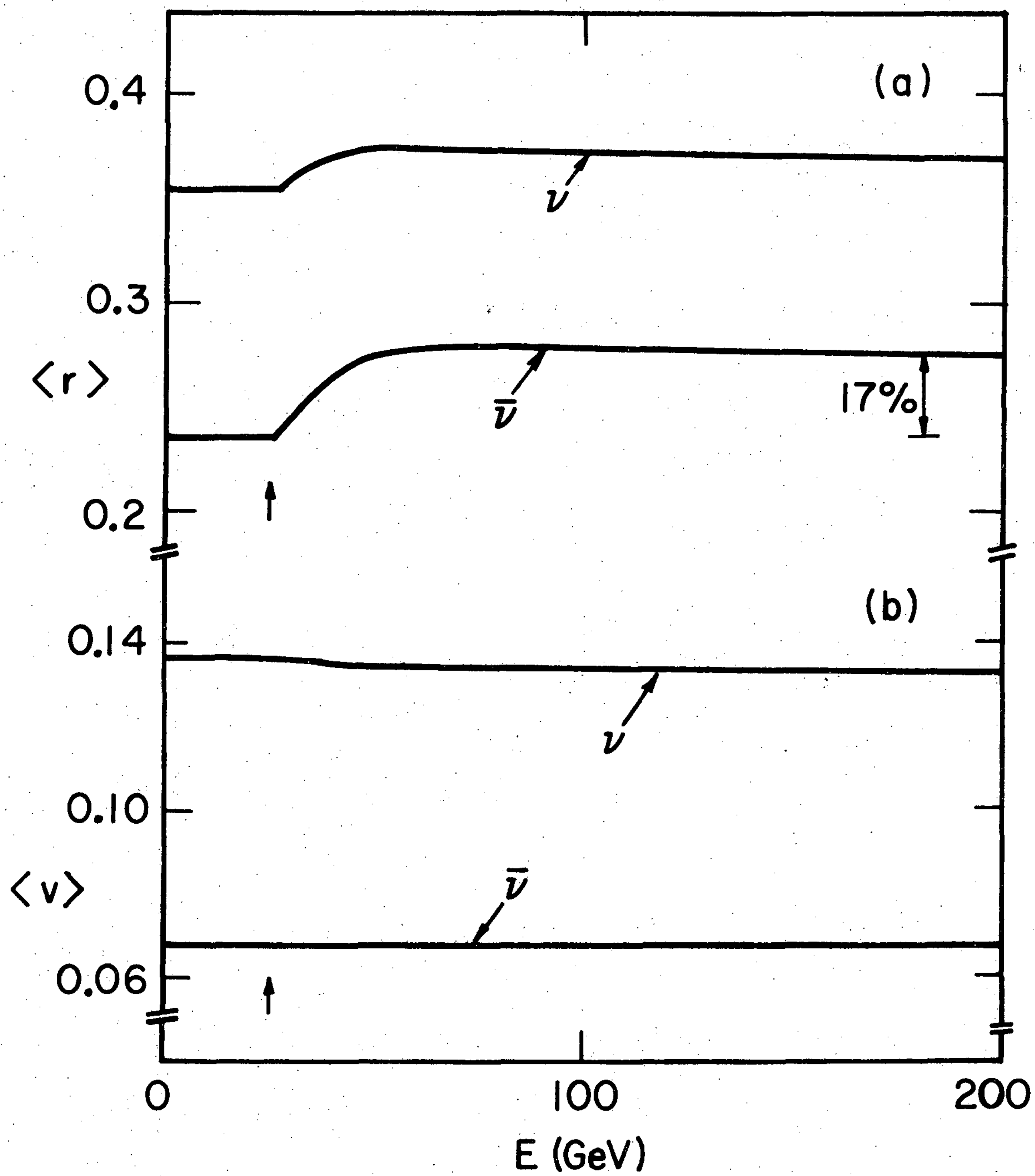
Fig. 1



XBL756-4331

Fig. 2



XBL756-4332

Fig. 3

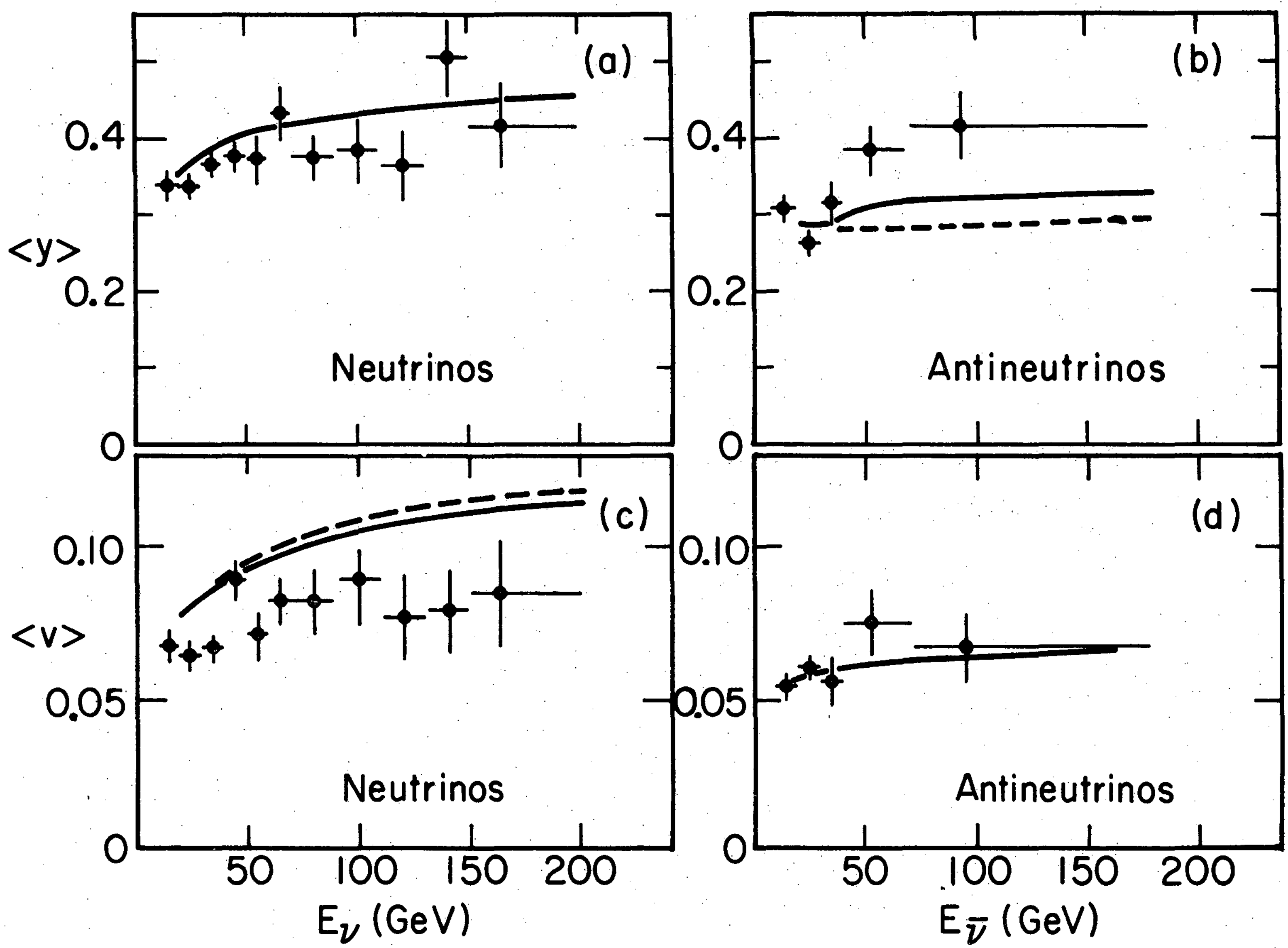


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Fig. 4

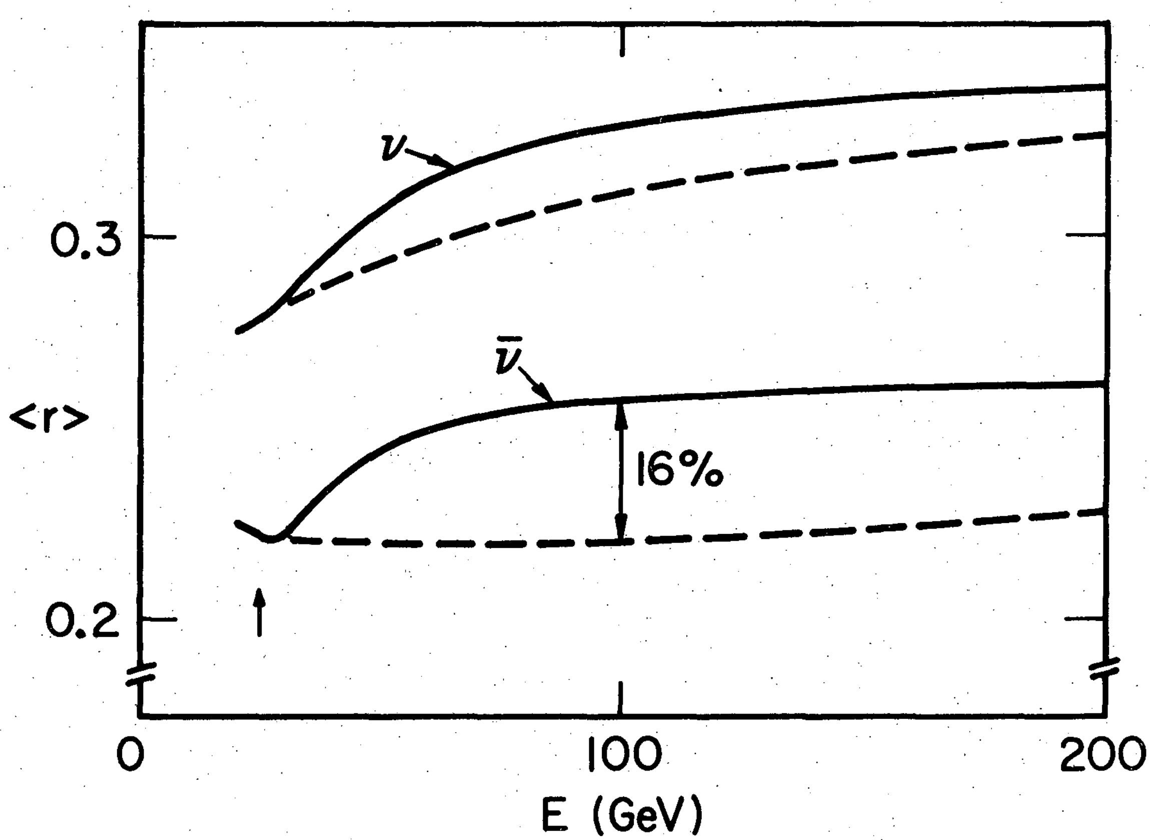

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Fig. 5

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