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Measurement of the Bjorken x and y distributions in neutral- and charged-current ν_μ interactions

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ABSTRACT

Distributions of the Bjorken scaling variables x and y, and the structure function $F_+(x)$, are presented both for neutral-current and for charged-current ν_μ interactions. The data were obtained using the Fermilab 15-foot neon bubble chamber exposed to a narrow-band ν_μ beam. Results are based on 151 neutral-current and 683 charged-current events. An important feature of the neutral-current analysis is the event-by-event reconstruction of the outgoing neutrino.

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There have been many studies of the deep inelastic charged-current reaction

$$\nu_\mu + N \rightarrow \mu^- + H \qquad (1)$$

where H represents the final-state hadronic system. To study the space-time structure of the current and its coupling to the hadronic constituents, an important tool has been the measurement of the Bjorken scaling variables x and y, defined by

$$x = Q^2/[2M(E_\nu - E_\ell)] \; ; \; y = (E_\nu - E_\ell)/E_\nu$$

where E_ν and E_ℓ are respectively the energies of the incoming neutrino and outgoing lepton, Q^2 is the four-momentum transfer between them, and M is the proton mass.

It is of fundamental importance to measure x and y also for the neutral-current reaction

$$\nu_\mu + N \rightarrow \nu_\mu + H. \qquad (2)$$

A basic problem, however, is that the outgoing neutrino in reaction (2) cannot be detected and therefore must be reconstructed. This is difficult to do in most neutrino experiments. We are aware of only two measurements of x for the neutral-current reaction (2). One[1] adopted methods similar to the present analysis, but was based on only 23 events, while the other[2] used a statistical unfolding method without reconstructing the outgoing neutrino on an event-by-event basis.

We report a measurement of x and y for both the reactions

(1) and (2). The experiment was carried out at Fermilab using the 15-foot bubble chamber exposed to a narrow-band, "dichromatic" ν_μ beam. The neutrinos originated from the two-body decays of momentum-selected secondary π^+ and K^+ mesons which were produced by 400 GeV protons in a beryllium target. The present data came from five separate runs in which the π^+ and K^+ momenta were set at 125, 140, 165, 200 and 250 GeV/c. The overall neutrino energy spectrum peaked at 50 and 120 GeV for π^+ and K^+ parents respectively, and the numbers of events from the two sources were in the ratio $\nu_\pi:\nu_K = 3:1$.

The bubble chamber was filled with a "heavy" neon-hydrogen mixture (59 atomic percent neon). The liquid had a radiation length of 40 cm, so that γ's from π^o decays underwent visible conversion. The liquid also had a hadron interaction length of 125 cm, while the chosen fiducial volume provided an average potential path length of 200 cm. Therefore hadrons usually interacted or stopped within the chamber, while muons left the chamber without interacting, thereby providing a simple way of distinguishing reactions (1) and (2). Events having a negative leaving track were assigned to reaction (1); if there was more than one such muon candidate in an event, the one with the highest momentum was selected as the muon.

A total of 98,000 pictures were taken, containing 2298 events in the fiducial volume. For every event, measurements were made of all the charged tracks as well as all the visible associated neutrals. From the radial vertex position of each

event the neutrino energy could be calculated[3] to about 10%, but was ambiguous between two values, since it was not known à priori whether the neutrino originated from π or K decay. To resolve this ambiguity the measured hadronic energy E_h was compared to the neutrino energy E_ν^π for the π-decay hypothesis; events with E_h smaller (greater) than $1.1E_\nu^\pi$ were assigned to the π(K) decay hypothesis. The accuracy of this method was tested using the charged-current events, for which the muon was measured as well as the hadrons, so that the entire final-state energy was known and could be compared to E_ν^π and E_ν^K. It was found that the above assignment was correct for 90% of the events. (The charged-current sample was also used to determine the effect on the scaling distributions of the residual misassignment).

To correct the measured hadronic energy for those neutrals which escaped undetected from the chamber, the charged-current sample was again used as a calibration. The requisite correction was 11% for $E_h < 20$ GeV, and then rose linearly to 35% at E_h = 100 GeV. This correction was applied to E_h for both reactions (1) and (2). For the charged-current events the corrected final-state energy then reproduced the calculated neutrino energy, with a σ of 17%.

In order to reduce the backgrounds in the neutral-current sample, the corrected hadronic energy was required to exceed one-tenth of the neutrino energy, and the hadronic momentum vector was required to make an angle less than 25° to the incoming neutrino. ν_e interactions were eliminated by removing events having an electron of energy greater than 1 GeV. The

charged-current data were treated identically for comparison. After these cuts, the sample consisted of 208 neutral-current and 683 charged-current candidates.[4]

For each event the outgoing lepton's four-momentum was reconstructed using energy and transverse momentum balance. The accuracy of the reconstruction was checked with the charged-current sample, for which it was found that the reconstructed lepton energy matched the measured muon energy with a σ of 17%.

The only significant background in the charged-current sample was due to pion punchthrough, i.e. if a π^- left the chamber without interacting, it could be incorrectly considered a μ^-. For each event in the neutral-current sample the punch-through probability was calculated by using the potential path length of each track and the known interaction length in the chamber liquid. This procedure gave a background of (8 ± 3)%, consistent with other calculations.[4] This method also permitted a determination of the x and y distributions of the background, so that corrections could be performed.

The neutral-current sample was contaminated by the interactions of neutral hadrons produced upstream of the bubble chamber. The sample was re-examined on the scan table to search for any activity, upstream of the interaction point, with which the event might be associated. A total of 57 events were eliminated as a result, reducing the neutral-current sample finally to 151 events. By subjecting a portion of the charged-current sample to the same examination, it was found that the probability of losing a real neutral-current event by random

association was 12%. Figure 1 shows the distance of the interaction point from the upstream wall of the chamber, i.e. the penetration distance of the neutrino into the chamber, for (a) the neutral-current sample, (b) the charged-current sample, and (c) the "neutral-current" candidates rejected because of upstream activity. For charged-current events the distribution reflects the uniform vertex density in the fiducial volume, while the rejected events show the attenuation expected for hadron interactions. For comparison we show in Fig. 1(d) the corresponding distribution for identified neutron interactions associated with events, i.e. the distance from the primary event vertex to the neutron interaction point. The similarity of Figs. 1(c) and 1(d) indicates that the rejected events are indeed mostly background.

To evaluate the residual neutron background, we assumed that it would have the shape of Fig. 1(c). We performed a fit to Fig. 1(a), describing it as a weighted superposition of Fig. 1(b) and 1(c). The free parameters in the fit were the amount of the residual background and the neutral-current to charged-current cross section ratio. The fit yielded a residual background of (15 ± 3)% and a cross section ratio of 0.27 ± 0.03.

Distributions of the scaling variables x and y were obtained both for neutral-current and charged-current events. As described above, the distributions were corrected for the punchthrough background, the neutron background, all of the cuts made on the data, and the misallocation of events between

$\nu(\pi)$ and $\nu(K)$. Corrections were also made for smaller backgrounds due to wide-band contamination in the narrow-band beam.[4] The final value of the neutral-current to charged-current cross section ratio was 0.29 ± 0.04, in good agreement with previous measurements.[5]

The final important step was to correct the scaling distributions for the effects of experimental resolution. There were two aspects to this problem: a) the neutral-current distributions needed to be corrected for the effects of using a reconstructed outgoing lepton. To do this, we used the charged-current events, which were analyzed using both a <u>reconstructed</u> and a <u>measured</u> μ^-. Correction matrices were derived to relate scaling variable distributions using reconstructed μ^- to those using measured μ^-. The matrices were then employed to correct the neutral-current distributions. It should be emphasized that this technique does not force the neutral-current distributions to have the same shape as the charged-current; only the correction to the reconstructed lepton is assumed to be the same. b) The distributions needed to be corrected for the effects of track measurement errors. Correction matrices were obtained by randomly changing the individual track parameters using the Gaussian errors calculated by the geometry program TVGP, reconstructing the distorted events, and comparing the new scaling variables to the original ones. After both corrections were made, the overall resolutions were $\sigma_x \sim .09$ and $\sigma_y \sim .06$. We therefore use a bin size of 0.1 for

the fully corrected distributions which are shown in Figure 2. The charged-current distributions use the measured rather than reconstructed μ^- for better resolution.

The final distributions are very similar for charged- and neutral-current events. The charged-current y distribution was fitted to the form $(1+B) + (1-B)(1-y)^2$, where $B = (Q-\bar{Q})/(Q+\bar{Q})$ is a measure of the coupling to the antiquarks of the sea. We obtained $B = 0.65 \pm 0.25$, in excellent agreement with the value of 0.68 measured in previous experiments.[6] The neutral-current y distribution was fitted to the Weinberg-Salam prediction[7] using $\sin^2 \theta_\omega = 0.222$[6] and $B = 0.68$. Both fits are shown in Figure 2.

The x distributions are related to the weak nuclear structure functions $F_2(x)$ and $xF_3(x)$ through the relation

$$(d\sigma/dx)_{\nu,\bar{\nu}} = (G^2 M E_\nu/2\pi)\ F_\pm(x)$$

where

$$F_\pm(x) = \frac{4}{3}\, a\, F_2(x) \pm \frac{2}{3}\, bxF_3(x).$$

Here $a = u_L^2+u_R^2+d_L^2+d_R^2$ and $b = u_L^2+d_L^2-u_R^2-d_R^2$ are combinations of left- and right-handed neutral-current couplings to the u and d quarks. (For charged-currents, a=b=1.) To obtain $F_+(x)$ it was necessary to normalize the x distributions using the total cross sections. For charged-current events we used our previously published[4] value of $\sigma/E_\nu = (0.62 \pm 0.05) \times 10^{-38}$ cm^2/GeV, while for neutral-currents we used $\sigma/E_\nu = (0.18 \pm 0.03) \times 10^{-38}$ cm^2/GeV, a value derived from our measurement of the ratio

$\sigma_{NC}/\sigma_{CC} = 0.29 \pm 0.04$ as described above. Figure 3 shows the distributions of $F_+(x)$ for our data, and indicates that the shapes for neutral- and charged-current events are consistent with each other.

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REFERENCES

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FIGURE CAPTIONS

Fig. 1: Distance of penetration of an incoming particle into the bubble chamber, for a) neutral-current events; b) charged-current events; c) rejected neutral-current candidates; and d) interactions of identified neutrons, for which the distance is the actual path length traversed. The vertical scale applies to sample (a). The other samples are normalized so that sample (a) equals the sum of sample (b) and either sample (c) or (d).

Fig. 2: Scaling variable distributions x and y for neutral- and charged current interactions. The distributions are fully corrected for all backgrounds, cuts, and the effects of experimental resolution. The outgoing lepton is measured for the charged-current events, but reconstructed for the neutral-current events. The solid lines are the results of fits described in the text.

Fig. 3: The weak nuclear structure function $F_+(x)$ for a) neutral-current, and b) charged-current events.

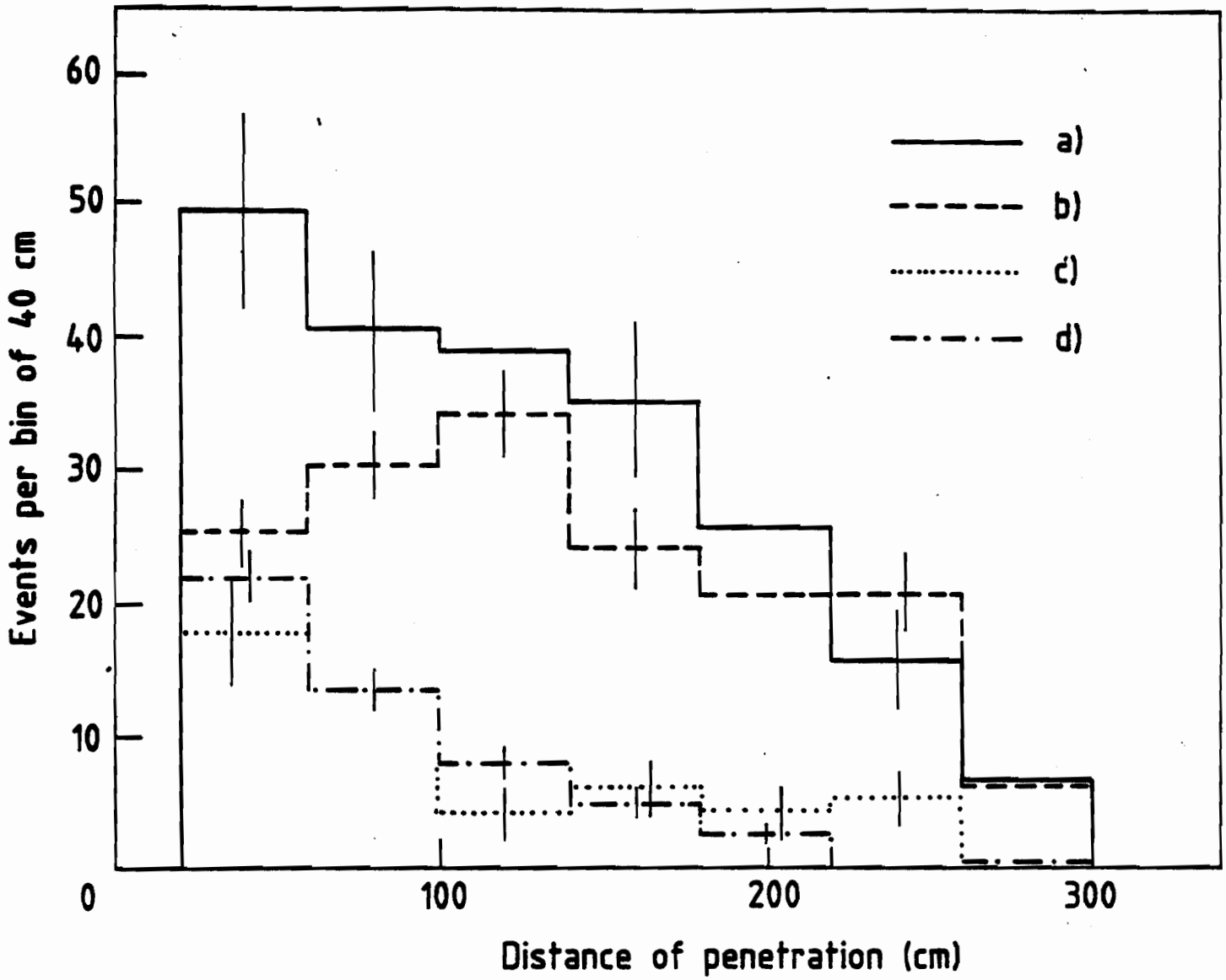
60
50
40
30
20
10
0
100
200
300
Events per bin of 40 cm
Distance of penetration (cm)
a)
b)
c)
d)

FIG. 1

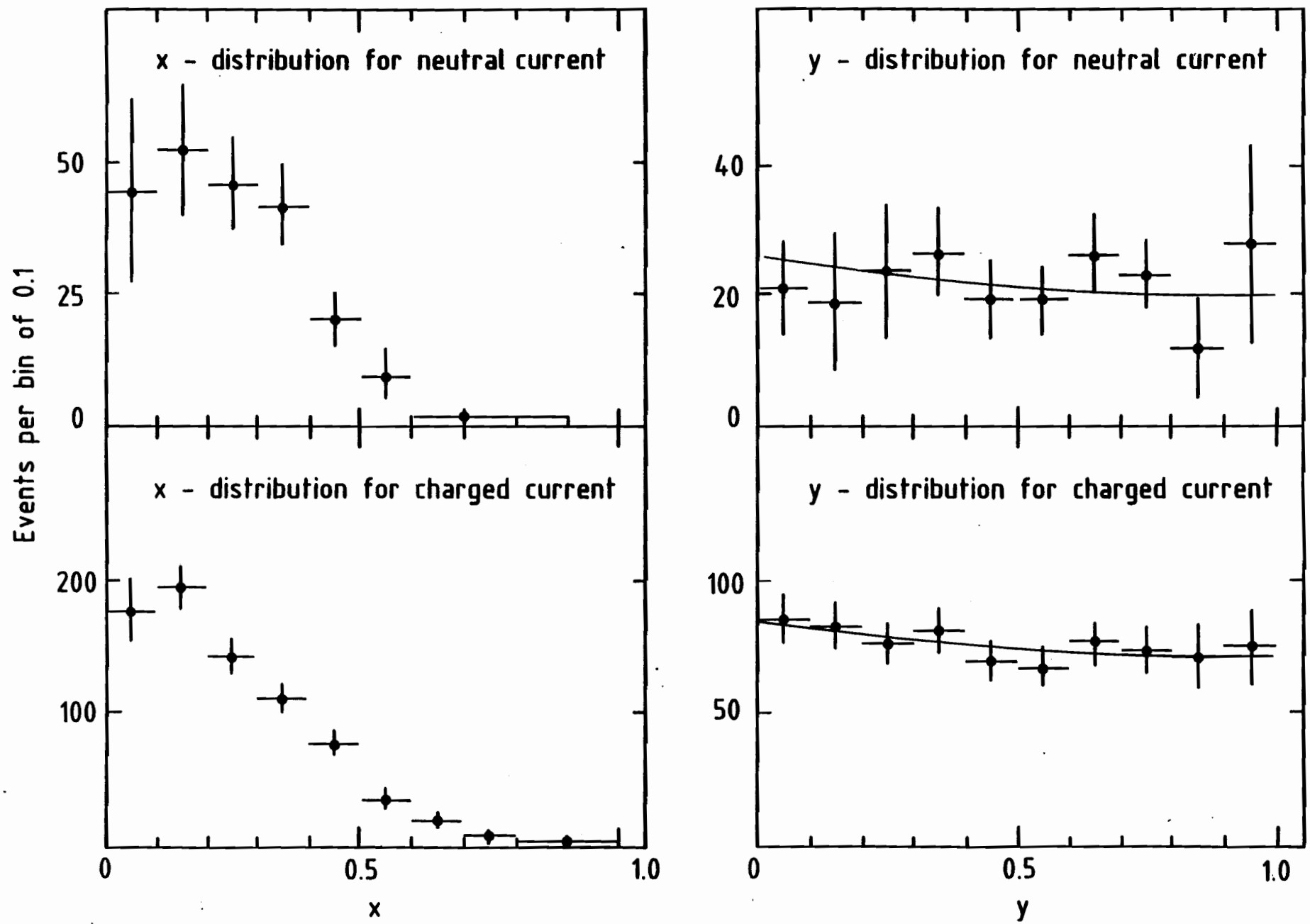
x - distribution for neutral current
y - distribution for neutral current
x - distribution for charged current
y - distribution for charged current
Events per bin of 0.1
50
25
0
40
20
0
200
100
100
50
0
0.5
1.0
x
0
0.5
1.0
y

FIG. 2

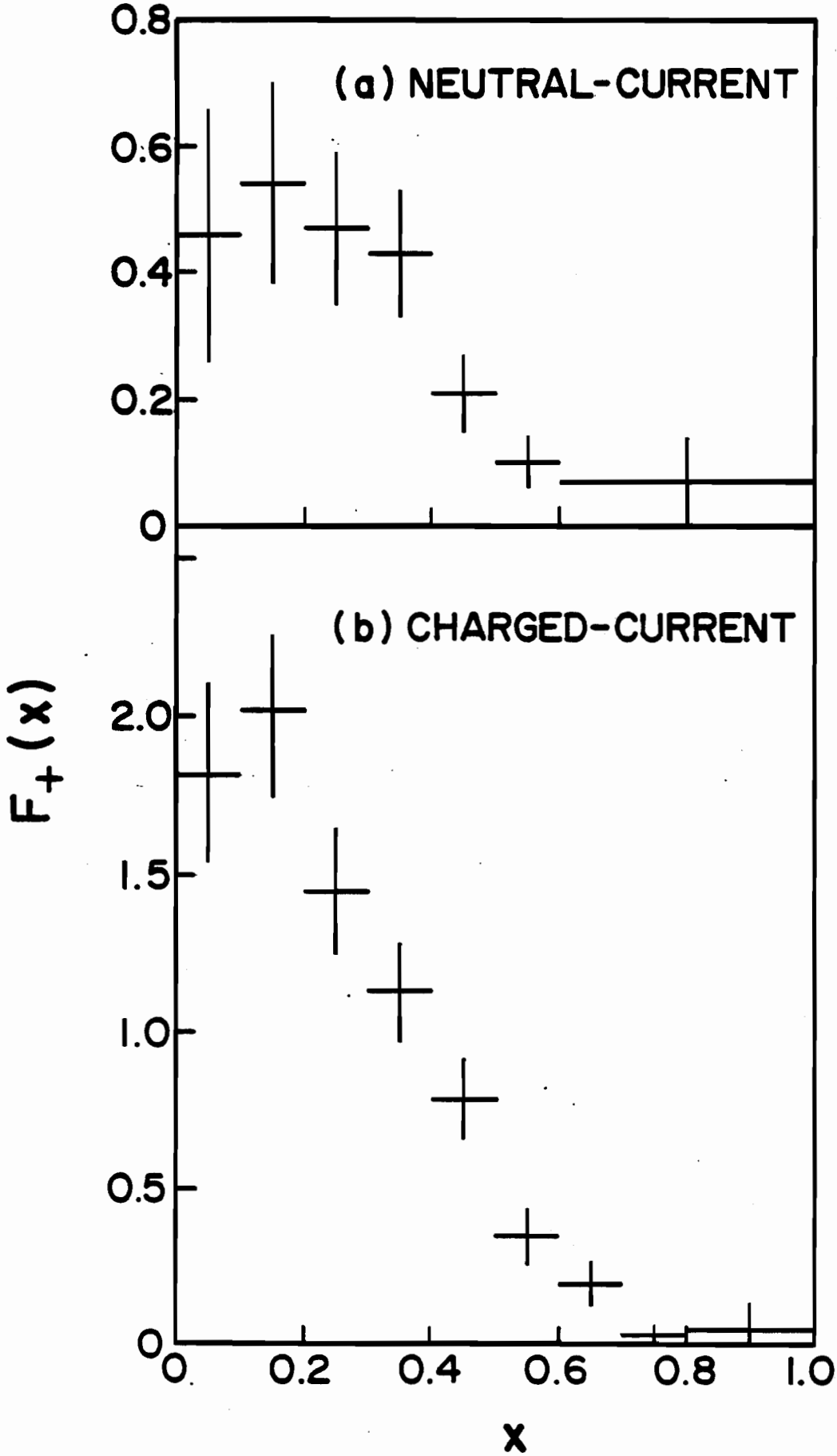
(a) NEUTRAL-CURRENT
(b) CHARGED-CURRENT
$F_+(x)$
x
0.8
0.6
0.4
0.2
0
2.0
1.5
1.0
0.5
0
0
0.2
0.4
0.6
0.8
1.0

FIG. 3