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Expt #98

PROPERTIES OF INCLUSIVE HADRON SPECTRA IN MUON NUCLEON SCATTERING AT 150 GeV/c*

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ABSTRACT

We have studied muon-produced hadrons from a deuterium target. The structure functions and the charge ratios are reported for neutrons; the transverse momentum and azimuthal distributions are reported for deuterons. The structure function for the neutron is similar to that of the proton. The charge ratio of produced hadrons follow the expectation of a simple spin ½ quark model. Transverse momentum results agree with those of lower energy and are similar to those from hadron-hadron interactions. No azimuthal anisotropy is seen.

In a previous paper[1] we reported measurements of the hadron spectra from virtual photon interactions with protons. In this paper we extend these measurements to neutrons. The data were obtained using the muon scattering facility at Fermilab and comprise 2.1×10^{10} muons incident on 8.4 gm/cm^2 of liquid hydrogen and 1.84×10^{10} muons incident on 20.1 gm/cm^2 of liquid deuterium.

The hadron invariant structure function for the neutron is $F_n(x')$:

$$F_n(x') = \int dp_T^2 \frac{1}{\pi} \frac{E^*}{(P^*_{max}{}^2 - p_T^2)^{1/2}} \frac{1}{\sigma} \frac{d^2\sigma}{dp_T^2 dx'} \qquad (1)$$

where $x' = p^*_{||}/(p^{*2}_{max} - p_T^2)^{\frac{1}{2}}$, is a Feynman scaling variable, and p_T, $p^*_{||}$ E^*, p^*_{max} are respectively the transverse momentum, longitudinal momentum, energy, and maximum momentum of a hadron in the center of mass system for the virtual photon and neutron. This center of mass energy squared is $s = 2M_n\nu + M_n^2 - q^2$ where M_n is the neutron mass, ν is the lab energy lost by the scattered muon and $-q^2$ is the mass squared of the virtual photon. $F_n(x')$ is derived from the corresponding deuteron and proton structure functions as follows:

We assume that the deuteron muon inclusive cross section $\sigma_D(q^2,s)$ is the sum of the neutron and proton cross sections. We also assume the hadrons per deuteron interaction are the sum of those from the neutron and the proton. This leads to

$$F_n(x') = \frac{\sigma_D}{\sigma_n} F_D(x') - \frac{\sigma_p}{\sigma_n} F_p(x'). \qquad (2)$$

The ratios σ_D/σ_n and σ_p/σ_n are functions of $\omega = 2\ m\nu/q^2$ and are taken from inelastic electron scattering experiments.[2] The muon inclusive data are consistent with these but have less accuracy. The hadron charge ratio is obtained in an analogous way.

The apparatus and methods were described in Ref. 1. The corrections applied to the data are the same except for the deuteron radiative correction and the increased rescattering in the denser deuterium. Detailed radiative corrections, beyond the subtraction of the elastic tail, have negligible effect on the results. Corrections for the Fermi motion of the nucleons in the deuteron or for the shadowing of one nucleon by the other are also negligible.

Figure 1 shows $F_n(x')$ for the neutron. The data show no significant variation with q^2 or s, and the structure functions are equal, within statistics, to those for the proton. Figure 2 shows the forward charge ratio N^+/N^- for the neutron plotted as a function of ω. Also shown are the proton data from this experiment and other proton and neutron data.[3] The value of ω used for our data is the average value for the events in the q^2-s ranges of Fig. 1. The solid lines in Figure 2 are fits to the data of Dakin et al. based on a simple quark model[4] of the proton and neutron. Our data are consistent with these fits. In this quark model the neutron and proton are composed of a sea of quark anti-quark pairs as well as valance quarks. At high ω most of the virtual photon interactions are expected to be with the quark sea which is charged symmetric. The similarity of the neutron and proton data at high ω and the fact that the charge ratios tend to one as ω increases is evidence for this sea.

The neutron and proton data are similar. From here on we treat the deuteron as if composed of two independent and equivalent nucleons. The rest of the results are from the deuterium data only.

It is of interest to compare the hadronic structure function for muon-nucleon scattering with that from electron-positron collisions. Figure 3 shows F(x') for the deuterium data compared to the analogous structure function for electron-positron annihilation.[5] The variable and structure function for annihilation is different in detail from F(x') used here but for x' > 0.2 is essentially the same. Table I describes the functions plotted. The similarity of the photon and annihilation data is striking. This feature is predicted by a quark model.[4]

Hadron production by scalar and transverse virtual photons can produce interference terms in the azimuthal distributions of hadrons about the direction of the virtual photon. Most generally we may write[6]

$$\frac{d\sigma}{d\phi_h} = A + \varepsilon B - \varepsilon C \cos 2\phi_h - 2\sqrt{\varepsilon+\varepsilon^2}\ D \cos\phi_h \qquad (3)$$

where ϕ_h is the azimuthal angle of the hadron about the virtual photon referenced to the azimuthal angle of the leptons and ε is the transverse polarization of the virtual photon. The data is binned as a function of p_T, x', q^2 and ε. No significant anisotropy is shown by the azimuthal distributions. Fig. 4 shows $d\sigma/d\phi_h$ for two ranges of q^2 and with x' cut to be clearly in the region of photon fragmentation. The data have $s > 20(\text{GeV})^2$ and are summed over all p_T and ε. Both are consistent with a constant distribution. Ravndal[6] showed that the absence of polarizations is consistent

with a spin ½ parton model.

To complete the description of the inclusive hadron distributions we have fitted the p_T^2 dependence of the differential structure function $(E_h/\sigma)(d^3\sigma/dp_h^3)$ as a function of x'. We have used the form

$$\frac{E_h}{\sigma}\frac{d^3\sigma}{dp_h^3} = \left(\frac{E_h}{\sigma}\frac{d^3\sigma}{dp_h^3}\bigg|_{p_T^2=0}\right)\cdot \exp\left\{\frac{-2bp_T^2}{1+(1+\frac{p_T^2}{M^2})^{\frac{1}{2}}}\right\} \qquad (4)$$

This is the transverse momentum distribution used in Ref. 1 but it is parameterized differently. M is mainly determined by the low x' data. We have used the value of M determined at x' = 0.15 as a fixed parameter in fits to the data at other x'. M is found to be 0.45 ± 0.05 GeV.

Some of the data and the results of the fits are shown in Figure 5. The chi-squares per degree of freedom for the fits are consistent with statistical fluctuations only. Also plotted are the directly measured average transverse momentum $\langle p_T \rangle$. Both b and $\langle p_T \rangle$ have a strong x' dependence; this behavior and the magnitudes of b and $\langle p_T \rangle$ are typical of hadron-hadron collisions.[7] The value of $(E_h/\sigma)(d^3\sigma/dp_h^3)$ at $p_T^2 = 0$ is in good agreement with the lower energy measurements of Bebek et al.[3]

We conclude the following:

1. The photon produced hadron inclusive distributions are consistent with a simple spin ½ quark model. This is shown by the charge ratios, the similarity of F(x') for both neutron and proton, the apparent lack of azimuthal hadron polarization, and the agreement of our measurements with those at lower energy.

2. Hadronic transverse momentum distributions produced by virtual photons are similar to those produced in hadron-hadron interactions.

We thank the staffs of Fermilab, of our home institutions and of the Rutherford Lab whose help made this work possible.

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   C. J. Bebek et al., Phys. Rev. Lett. 34, 759 (1975).

4. J. T. Dakin and G. J. Feldman, Phys. Rev. 8D, 2862 (1973).

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5. R. Schwitters, Proc. 1975 Intl. Symp. on Lepton and Photon Interactions at High Energies (1975), Stanford University.

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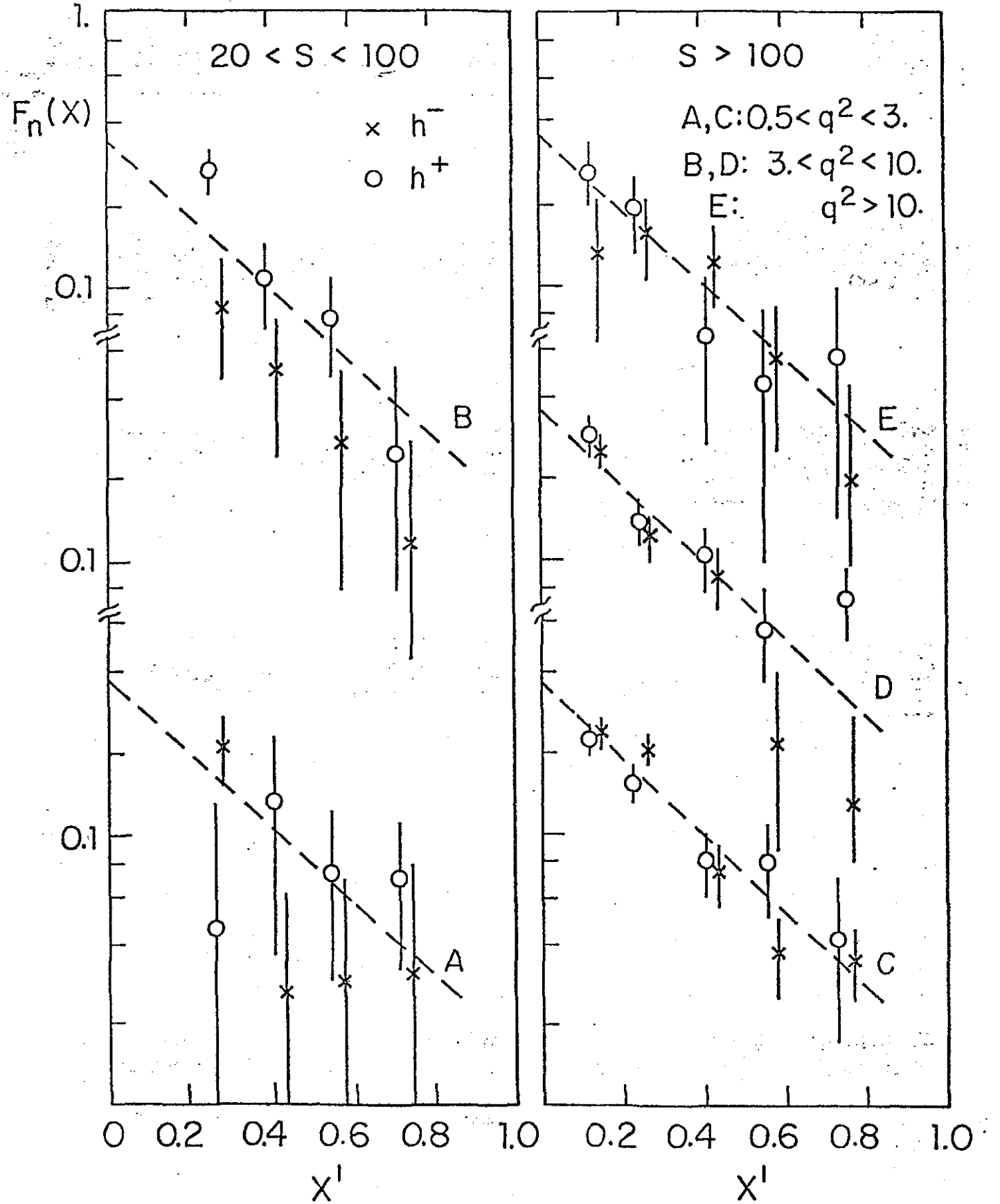
7. P. Bosetti et al., Nucl. Phys. B54, 141 (1973).

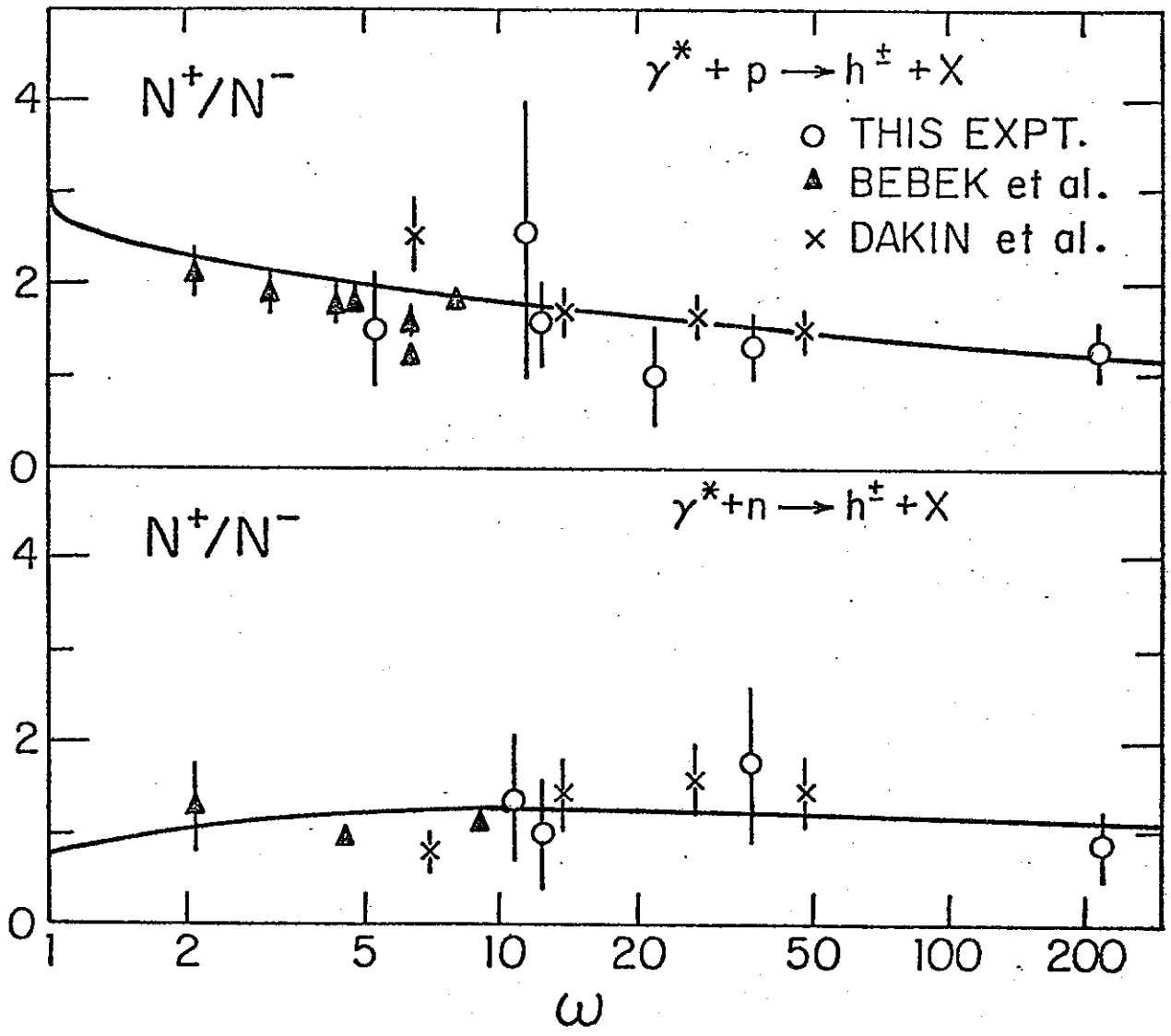
TABLE I

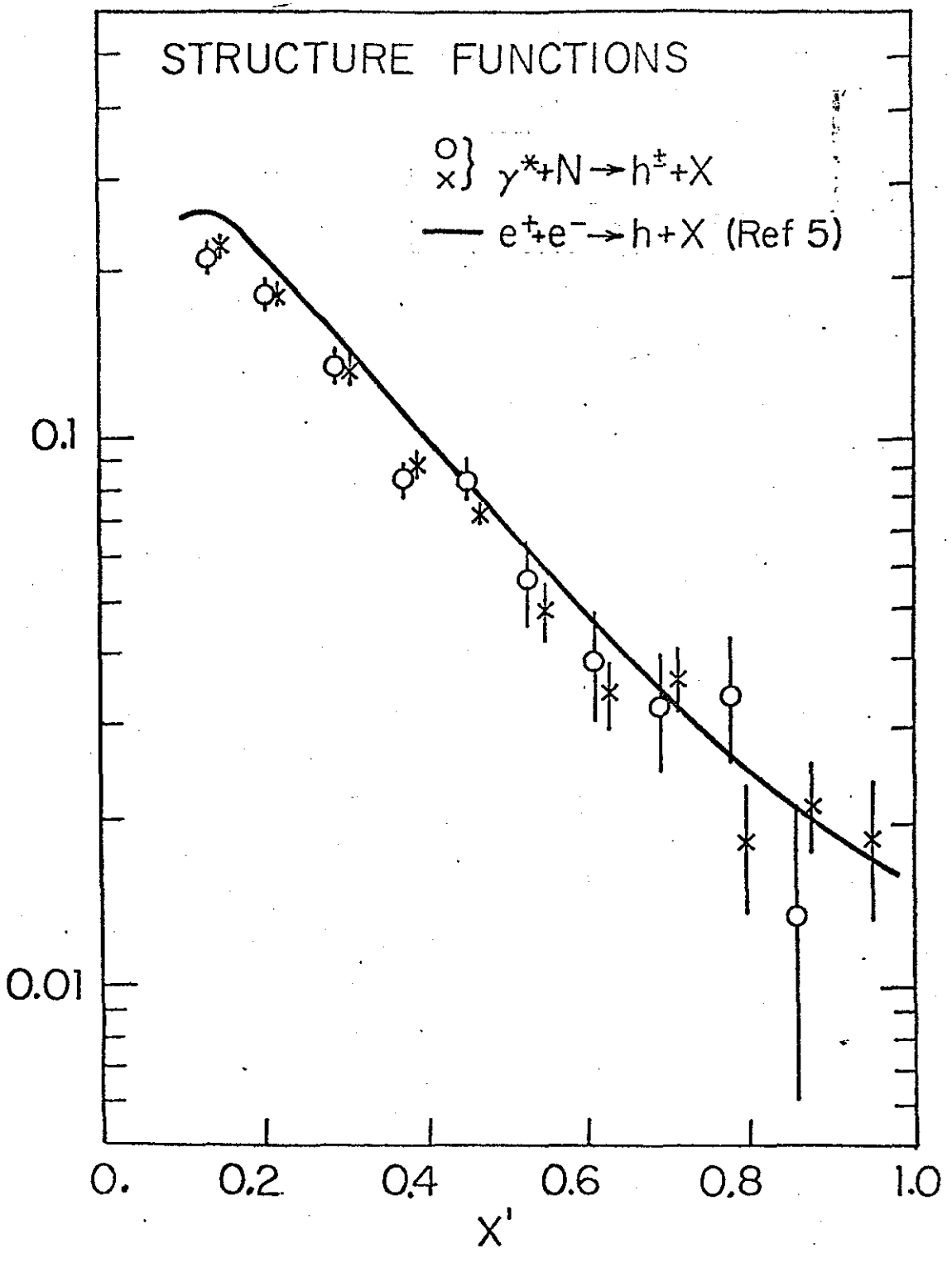
DESCRIPTIONS OF STRUCTURE FUNCTIONS

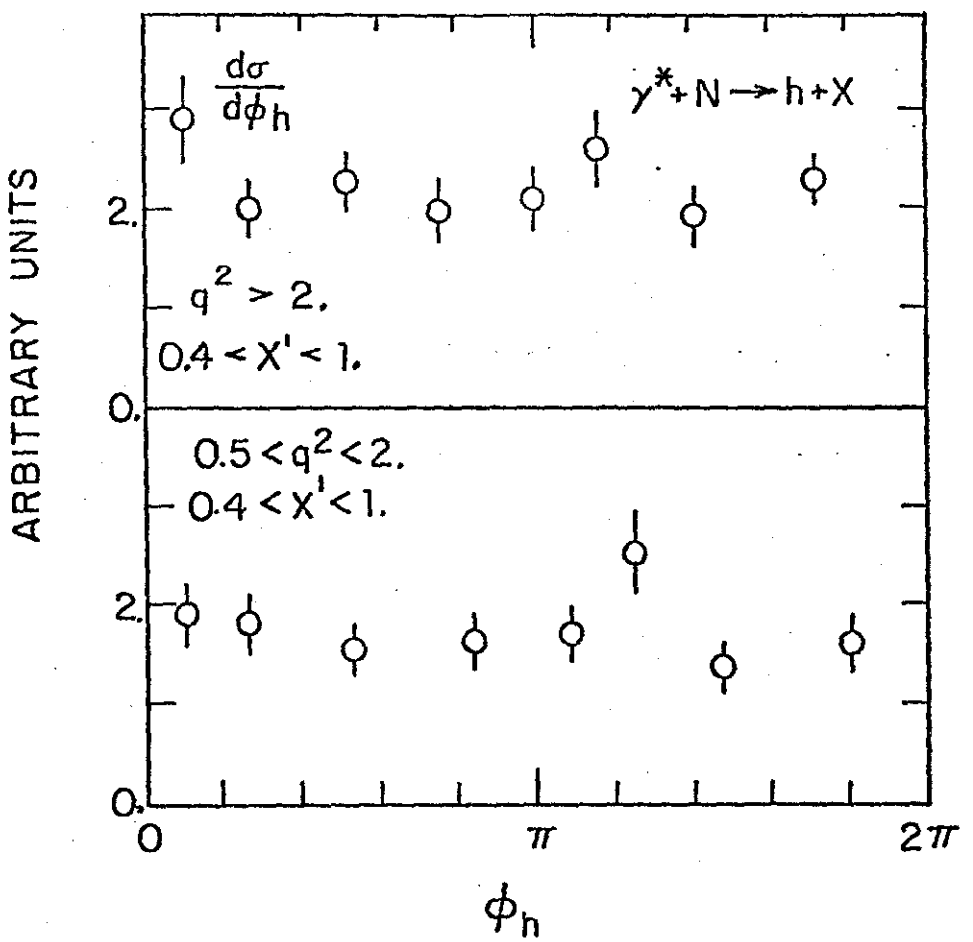
Interaction	Structure Function	Variable	CM Energy
$\gamma^* + N \rightarrow h^{\pm} + x$	$F(x')$	$x' = \dfrac{p^*_{\parallel}}{(p^{*2}_{max} - p_T^2)^{1/2}}$	$s > 100\ GeV^2$
$e^+ + e^- \rightarrow h + x$	$\dfrac{1}{4\pi\sigma} x \dfrac{d\sigma}{dx}$	$x = \dfrac{2p}{E_{cm}}$	$s = 55\ GeV^2$

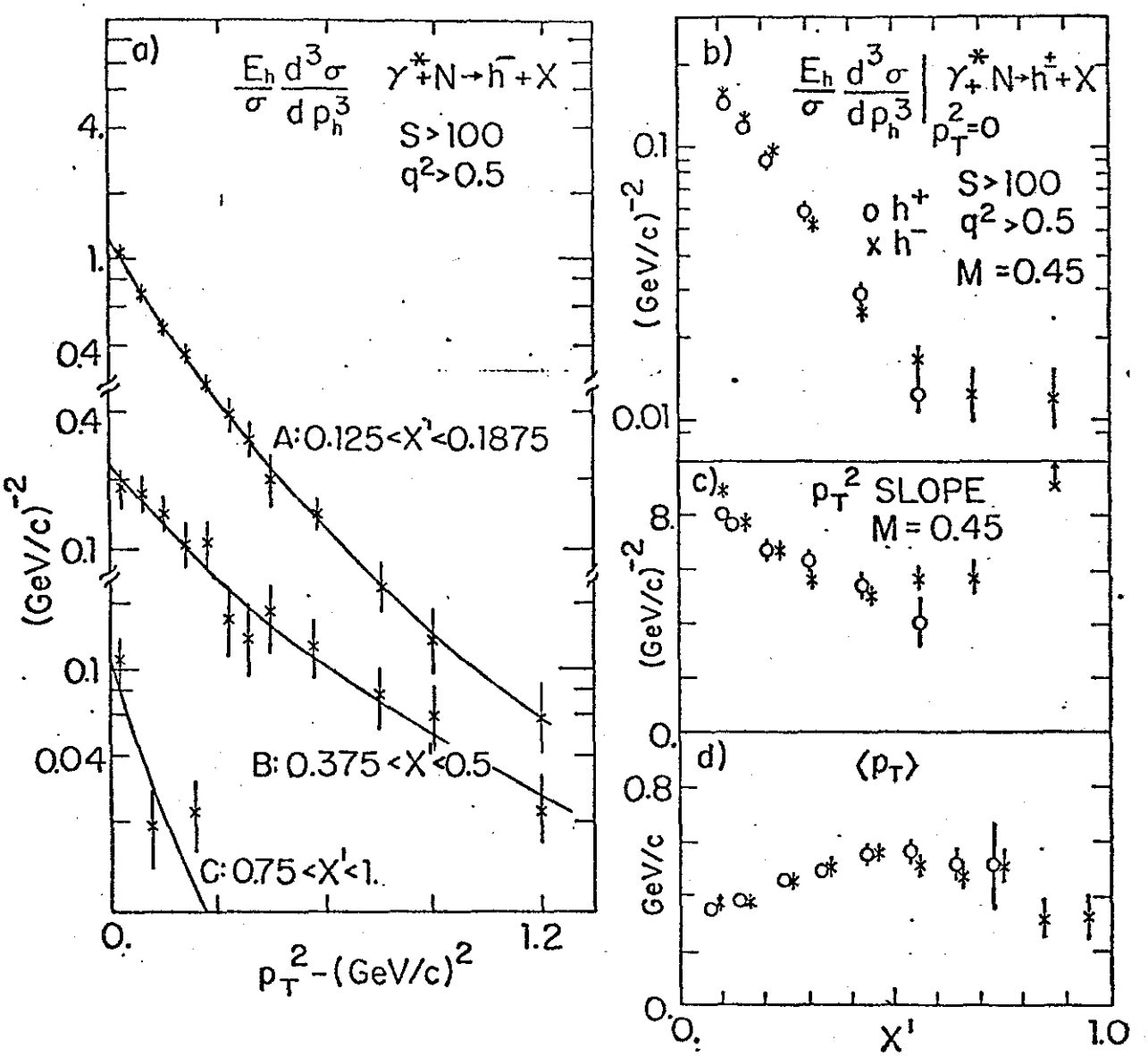
LIST OF FIGURES


1.
0.1
0.1
$F_n(X)$
20 < S < 100
× h^-
○ h^+
B
A
S > 100
A,C: 0.5 < q^2 < 3.
B,D: 3. < q^2 < 10.
E: q^2 > 10.
E
D
C
0
0.2
0.4
0.6
0.8
1.0
X'
0.2
0.4
0.6
0.8
1.0
X'


N^+/N^-
$\gamma^* + p \rightarrow h^\pm + X$
THIS EXPT.
BEBEK et al.
DAKIN et al.
N^+/N^-
$\gamma^* + n \rightarrow h^\pm + X$
4
2
0
4
2
0
1
2
5
10
20
50
100
200
ω


STRUCTURE FUNCTIONS
γ*+N→h±+X
e⁺+e⁻→h+X (Ref 5)
0.1
0.01
0.
0.2
0.4
0.6
0.8
1.0
X'


ARBITRARY UNITS
dσ/dφh
γ*+N→h+X
2.
q² > 2.
0.4 < X' < 1.
0.
0.5 < q² < 2.
0.4 < X' < 1.
2.
0.
0
π
2π
φh


a)
$\frac{E_h}{\sigma}\frac{d^3\sigma}{dp_h^3}$ $\gamma^*_+N\to h^-+X$
S>100
q^2>0.5
A: 0.125<X'<0.1875
B: 0.375<X'<0.5
C: 0.75<X'<1.
4.
1.
0.4
0.4
0.1
0.1
0.04
0.
1.2
p_T^2-(GeV/c)^2
(GeV/c)$^{-2}$
b)
$\frac{E_h}{\sigma}\frac{d^3\sigma}{dp_h^3}$ $\gamma^*_+N\to h^\pm+X$
p_T^2=0
o h^+
x h^-
S>100
q^2>0.5
M=0.45
0.1
0.01
(GeV/c)$^{-2}$
c)
p_T^2 SLOPE
M=0.45
8.
0.
(GeV/c)$^{-2}$
d)
$\langle p_T\rangle$
0.8
0.
GeV/c
0.
X'
1.0