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ABSTRACT

The results of a study of gamma production in antineutrino-nucleon interactions observed in the Fermilab 15-ft bubble chamber filled with a neon-hydrogen mixture are presented. From a sample of 706 gamma rays we obtained the dependence of the average number of produced π^0's on negative multiplicity, momentum transfer and hadronic invariant mass. We find that the mean transverse momentum of the gamma rays is independent of the above variables but has an asymmetric distribution with respect to the Feynman variable x. The invariant gamma cross section distributions, the distribution function D for π^0's and the energy spectrum of π^0's reconstructed from the gamma spectrum are also reported.

I. INTRODUCTION

The investigation of semi-inclusive processes in deep inelastic lepton-hadron interactions is important because it contributes to the understanding of the parton structure of hadrons.[1] An analysis of gamma production in charged current antineutrino reactions is presented in this paper.

The data are based on an exposure of 74,400 pictures in the Fermilab 15-ft bubble chamber filled with a hydrogen-neon mixture containing 21 at.% of neon. The density of this mixture is 0.3 g cm^{-3} and the radiation length is 100 cm.

The chamber was exposed to a broad-band double-horn-focused antineutrino beam. An absorbtive plug downstream of the target was used to suppress the neutrino contamination to less than 4% of the $\bar{\nu}$ flux. The mean proton intensity was (0.8 - 0.9) x 10^{13} protons per pulse with a proton energy of 300 GeV.

II. DATA

For the analysis of gamma production, 783 charged current antineutrino interactions with an energy in excess of 10 GeV were selected. The fiducial volume for the antineutrino events was a sphere of radius R = 165 cm centered in the chamber with the following additional two cuts: 1) a horizontal plane at z = 105 cm and 2) the requirement of a 60 cm downstream potential length. An additional, larger, fiducial volume for gammas was defined consisting of a sphere of radius R = 175 cm centered in the chamber with the two additional cuts: 1) a horizontal plane at z = 115 cm and 2) a horizontal plane at z = -170 cm. These fiducial volumes were chosen such that the measured length of a forward going charged track of high energy from the primary antineutrino interaction would be in excess of 60 cm and such that the length of a charged track from a neutral vertex will exceed 15 cm.

The hadron energy was corrected for losses from unmeasured neutrals by a method based upon the imbalance of the measured transverse momentum.[2] This correction averaged about 25% of the hadron energy. Positive muon candidates were identified by either finding a match to a track projected through the external muon identifier (EMI) or by a kinematic method.[3]

Inside the larger fiducial volume 706 electron-positron pairs were selected which were associated to the primary vertex according to the prescription that $D/\Delta D$ is less than 4. D is defined as the perpendicular distance from the primary vertex to the reconstructed line of flight of the photon. This selection criteria was based upon a study of a sample of gamma rays with kinematical fits to the primary vertex. The loss of associated gammas was found to be less than 1%, with a background of accepted but unassociated gammas of about 1%.

A calculation of the conversion probability for gammas must take into account losses both from conversions outside the fiducial volume and from conversions close to the primary vertex which are obscured by the presence of charged primary tracks. A minimum projected conversion length of 3 cm was imposed to permit corrections for the conversions close to the primary vertex. The pair creation cross section used for the calculations of conversion probabilities as a function of the gamma laboratory momentum is found in Ref. 4. Corrections for scanning and measuring inefficiencies were also included. Low energy gammas require special attention because the low scanning efficiency found for such low energy gammas is aggravated by the simultaneous fall-off of the pair-production cross section at these low energies. The correction[5] made for losses of low energy gammas ($E_\gamma < m_{\pi^0}/2$) is based upon the logarithmic symmetry of the gamma energy spectrum about the value of $E_\gamma = m_{\pi^0}/2$. In making this correction the assumption is made that the principal source of gammas is the decay of π^0's.

The mean weight after all of the above corrections of gammas used in the sample was about 2.7.

Many bremsstrahlung photons are found in the hydrogen-neon mixture. In Fig. 1(a) the gamma-gamma invariant mass spectrum is shown. The large background in the region $M_{\gamma\gamma}$ less than m_{π^0} arises from bremsstrahlung gammas which accidentally associate with the primary vertex. The bremsstrahlung photons may be removed from the sample by making use of the fact that the angle between the bremsstrahlung photon and its parent electron is in fact small.

A cut parameter $c_{cut} = 1 - \cos\theta$ has been defined where θ is the angle between two gammas. An experimental determination of an appropriate value of c_{cut} was made by examining the shape of the gamma-gamma mass spectrum as a function of this parameter for two different cases. 1) When the two gammas are both found in the same frame and could, therefore, be from a parent π^o and 2) When the two gammas are chosen from different frames, in which case only the closest gammas to the vertex were taken in each frame so that no bremsstrahlung gammas were included in the sample. The asymmetry in the gamma-gamma mass distribution about the π^o mass, as a function of c_{cut} is shown in Fig. 2. For the second case, where there is no possibility of a bremsstrahlung gamma being considered, a constant value is seen, as would be expected. For the case of gammas chosen from the same frame, there is a strong rise in the relative number of low invariant mass pairs beginning at $c_{cut} = 0.004$ which may be attributed to the presence of bremsstrahlung gammas in the sample. Therefore a value of $c_{cut} = 0.004$ was chosen for the cut values and a loss of about 3% is estimated in the data if all the gammas actually came from π^o decay.

III. MEAN MULTIPLICITY

The average number of π^o's per primary interaction with all corrections was calculated under the assumption that all gamma's originated from π^o decay; that is $\sigma(\gamma) = 2\sigma(\pi^o)$. The mean number of produced π^o's is then

$$< \pi^o > = < n_\gamma >/2 = 1.20 \pm 0.05$$

where $< n_\gamma >$ equals the total number of weighted γ's divided by the total number of μ^+ events.

This result agrees within the experimental error with the result calculated from the gamma's invariant mass distribution:

$$< \pi^{o} >_{\gamma\gamma} = 1.1 \pm 0.1.$$

This last number is calculated using the $M_{\gamma\gamma}$ background distribution obtained using γ's from different frames, normalized to the data in the $M_{\gamma\gamma} > M_{\eta}$ region. This agreement lends support to the above assumption made with respect to the source of gamma production and the accuracy of the previously described cut on bremsstrahlung photons.

The variables Q^2, W, x, P_t and Z have been used to analyze the data, where Q^2 is the square of the four-momentum transfer between the antineutrino and the mu-plus, x is the Feynman variable $x = 2\, P_L^*/W$, P_t and P_L^* are the transverse and longitudinal momentum of the gamma in the rest frame of the recoiling hadron system (whose invariant mass is W), and Z is the fraction of the hadronic energy carried by the gamma.

In the region x > 0.0 the quantity

$$V = \int_0^1 \{ D_d^{\pi^+}(Z) - D_d^{\pi^-}(Z) + D_d^{K^+}(Z) - D_d^{K^-}(Z) \} dZ$$

measures the charge of the forward going fragmenting d-type quark. Here the D's are the quark fragmentation function of Field and Feynmann[1]. We have used our present data on π^o production plus our previous data on negative hadron[6] (h^-) and neutral strange particle production[7] to calculate V. We assume that in the forward direction (x > 0.0) we have equal production of K^+, K^-, K^o, and $\bar{K}^o$ and that in the backward direction (x < 0.0) we have equal production of ΛK^+ and $\Lambda\bar{K}^o$. Using these assumptions and the relations

$$D_d^{h^-} = D_d^{\pi^-} + D_d^{K^-} \text{ and } (D_d^{\pi^+} + D_d^{\pi^-})/2 = D_d^{\pi^o} \text{ we can evaluate}$$

$$V = 2 < \pi^o > - 2 < h^- > + 2 < K_s^o > - \frac{< \Lambda >}{2} = -0.46 \pm 0.13$$

where $< \pi^o >$ and $< h^- >$ are the mean π^o and h^- multiplicities in the $x > 0$ direction respectively and $< K_s^o >$ and $< \Lambda >$ are the total mean K_s^o and Λ multiplicities respectively. This value agrees with the theoretical prediction[1] $V = -0.40$.

The correlation between π^o's and negatively charged particles at the primary vertex is shown in Fig. 3(a,b) for the following two regions of W: 1) W less than 4 GeV, and 2) W greater than 4 GeV. A linear fit to the experimental points yields the following slopes:

$$\alpha_1 = 0.05 \pm 0.06 \ (\chi^2/ND = 2.5/3) \text{ and}$$
$$\alpha_2 = 0.05 \pm 0.10 \ (\chi^2/ND = 0.4/3).$$

The values thus obtained for these slopes are in agreement with those found in hadronic experiments.[8]

The yield of π^o's per interaction as a function of W^2 is shown in Fig. 4, where it may be seen that these data agree within experimental errors with those from pion-nucleon interactions[9,10,11] A fit of these data to the form:

$$< \pi^o > = a + b \ln W^2$$

for W^2 greater than 4 GeV^2 yields:

1) $a = -0.37 \pm 0.17$

2) $b = 0.65 \pm 0.07$ with $(\chi^2/ND = 21/8)$.

The slope thus obtained is similar to that found in previous studies of negative hadron production.[6]

The yield of π^o's as a function of Q^2 is shown in Fig. 5. A linear fit of the data in the same two regions of W yields a result with slopes:

$\alpha_1 = 0.32 \pm 0.05$ $(\chi^2/ND = 4.1/4)$ and

$\alpha_2 = 0.31 \pm 0.10$ $(\chi^2/ND = 4.9/4)$.

The mean multiplicity of π^o's is thus only weakly dependent on Q^2 and its behavior is similar in the two different regions of W.

IV. INCLUSIVE GAMMA SPECTRA

We define the invariant cross section as:

$$F(x, P_t^2) = \frac{2P_\gamma^*}{\pi W} \frac{1}{N_{\bar{\nu}N}} \frac{d^2N_\gamma}{dx\, dP_t^2}$$

where $N_{\bar{\nu}N}$ is the total number of charged current antineutrino nucleon events N_γ is the number of inclusive gammas, and the other variables are as defined above.

The symbols $F_1(x)$ and $F_2(P_t^2)$ are defined to denote the integrals of $F(x, P_t^2)$ over P_t^2 and x respectively. $F_1(x)$ is shown in Fig. 6 first for two regions of Q^2 (Q^2 less than $2(GeV/c)^2$ and Q^2 greater than $2(GeV/c)^2$) and second for the same two regions of W defined above (W less than and greater than 4 GeV). The production cross section for gammas is seen to be larger in the central x region and increases for the regions of higher Q^2 and W. The increase in the γ production cross section with increasing Q^2 appears to be larger than that observed for negative hadron production.[6]

The data for the $F_2(P_t^2)$ distribution (Fig. 7) are well fit by the same parameterization as used in hadron experiments[8] which is:

$$F_2(P_t^2) = A\, P_t^{-1}\, e^{-P_t^2/B}.$$

When fit over the region $0 < P_t^2 < 0.4$ the value for B is found to be $B = 0.164 \pm 0.025$ ($\chi^2/ND = 15/17$), which agrees well with the value of $B = 0.162$ reported by hadron experiments.[12] The fitted curve is shown as the solid line in Fig. 7.

The dependence of $< P_{out} >$ (the average value of the gamma transverse momentum perpendicular to the $\bar{\nu}\mu^+$ plane) on Q^2, W^2 and x is investigated in Figs. 8(a), (b) and (c) respectively. $< P_{out} >$ is independent of Q^2 and W^2. A fit of the data to the form

$< P_{out} > = a + b \ln Q^2$ in the two regions of W used above (W less than and greater than 4 GeV) yields the following similar values for a and b: for W less than 4 GeV

$$a_1 = 0.093 \pm 0.008$$
$$b_1 = -0.008 \pm 0.007 \quad (\chi^2/ND = 15/18)$$

and for W greater than 4 GeV

$$a_2 = 0.104 \pm 0.011$$
$$b_2 = -0.008 \pm 0.007 \quad (\chi^2/ND = 6.8/8).$$

For the region $Z > 0.1$ the fit yields:

$$a = 0.15 \pm 0.01$$
$$b = 0.03 \pm 0.01 \quad (\chi^2/ND = 26/8).$$

In this region the mean value of $< P_{out} >$ has increased, but the slope remains approximately zero. The correlation between x and $< P_{out} >$ is seen in Fig. 8(c) and is possibly asymmetric about $x = 0.0$.

V. π^o SPECTRA

The Kopylov method[13] was used to calculate the π^o energy spectrum from the observed gamma spectum. In Fig. 9 the π^o spectrum thus obtained is compared with the π^- spectrum. The behavior of the

π^o and π^- spectra are similar within experimental error out to an energy of 3 GeV.

The spectra for π^o and π^- as a function of Z are shown in Fig. 10. The π^o fragmentation function was obtained using π^o's from gamma-gamma combinations in the region $0.1 < M_{\gamma\gamma} < 0.17$ GeV. These distributions are adequately described by the function exp(-Bz) with

$$B_{\pi^o} = 6.1 \pm 0.5 \quad (\chi^2/ND = 12/7) \text{ and}$$
$$B_{\pi^-} = 6.4 \pm 0.2 \quad (\chi^2/ND = 19/17).$$

Thus the fragmentation functions for π^o and π^- are identical within experimental error out to $Z = 0.8$.

VI. CONCLUSION

We have studied the gamma ray production resulting mainly from π^o decays in charged current antineutrino interactions. Using this information we have been able to obtain correlations between neutral and negative pions, and the dependence of the π^o yield on the invariant mass of the recoiling hadron system W and the square of the four-momentum transfer Q^2. We find that the mean transverse momentum of the gamma is independent of Q^2 and W and that the behavior of the invariant cross sectionsas a function of x and P_t are similar to those in hadronic reactions. These results, as do our previous results from semi-inclusive π^- production, imply that in antineutrino interactions the hadronic vertex has only a small "memory" of the details of the leptonic vertex.

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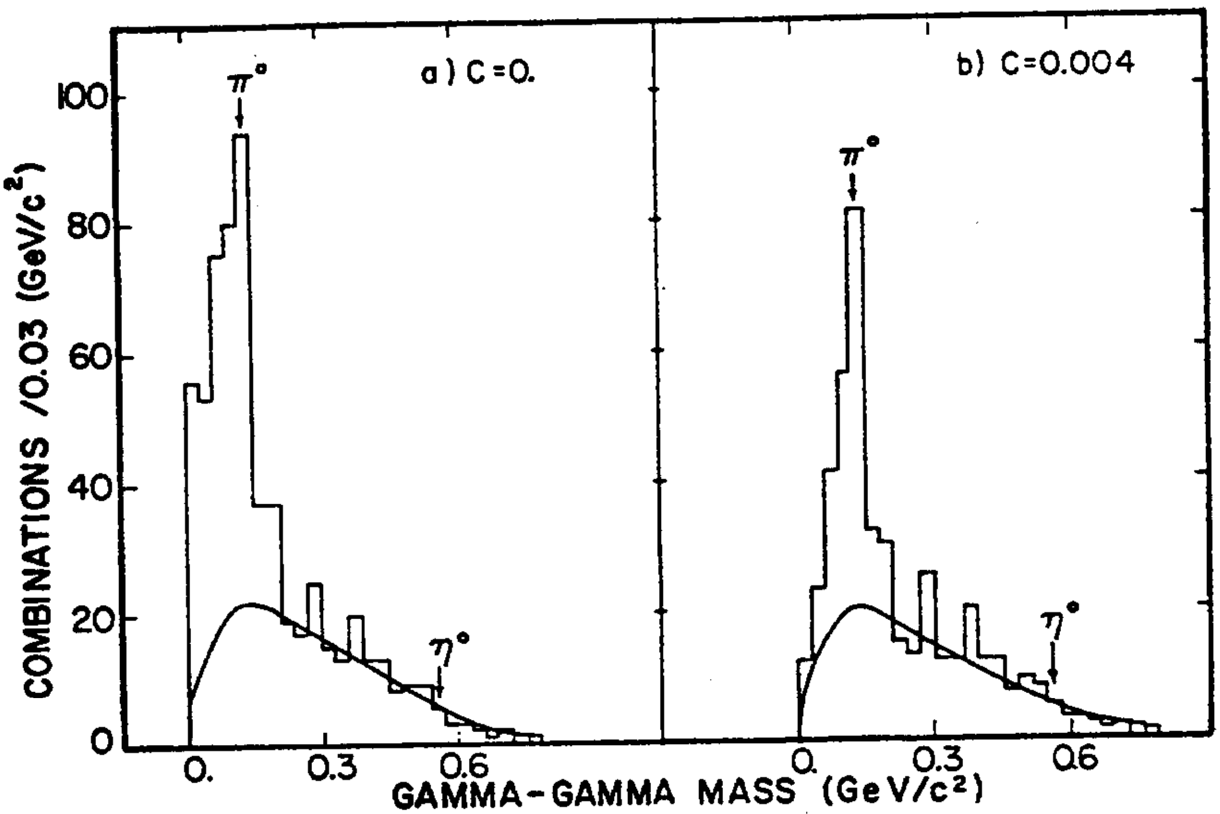

Fig. 1. Gamma-gamma effective mass spectrum (a) without cut, (b) with cut parameter c = 0.004.

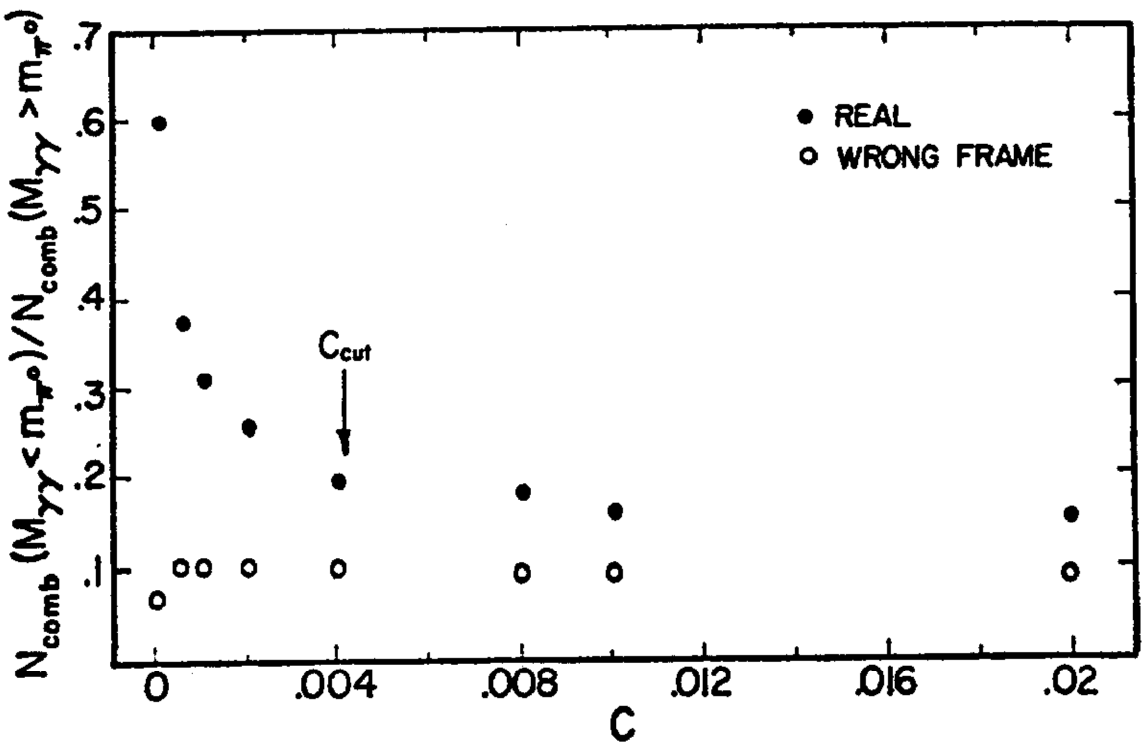

Fig. 2. The relation $R = N(M_{\gamma\gamma} < m_{\pi^o})/N(M_{\gamma\gamma} > m_{\pi^o})$ as a function of cut parameter c for real combinations and for combinations from wrong frame.

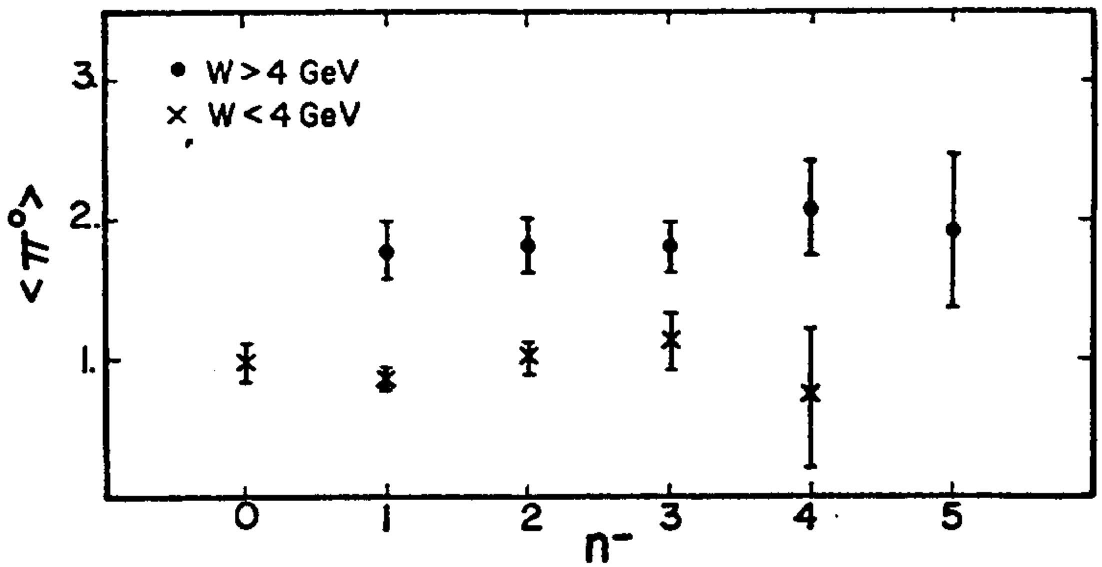

Fig. 3. Mean number of produced π^0's per antineutrino interaction as a function of number of negatively charged particles for two regions of W.

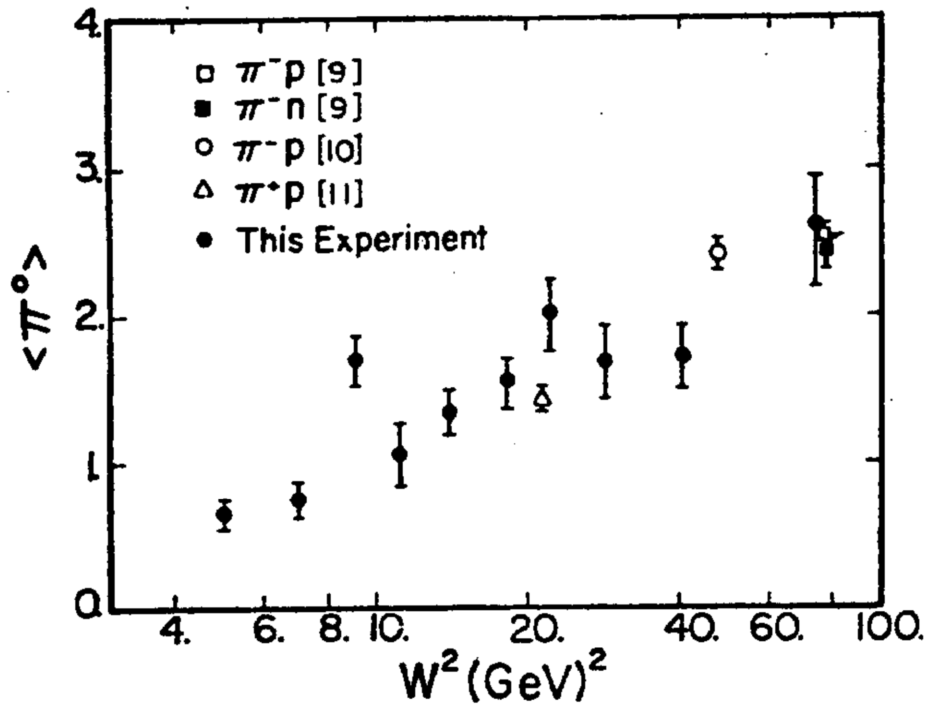

Fig. 4. The average number of π^0's as a function of the hadronic mass-squared W^2. The data of pion-nucleon experiments are shown.

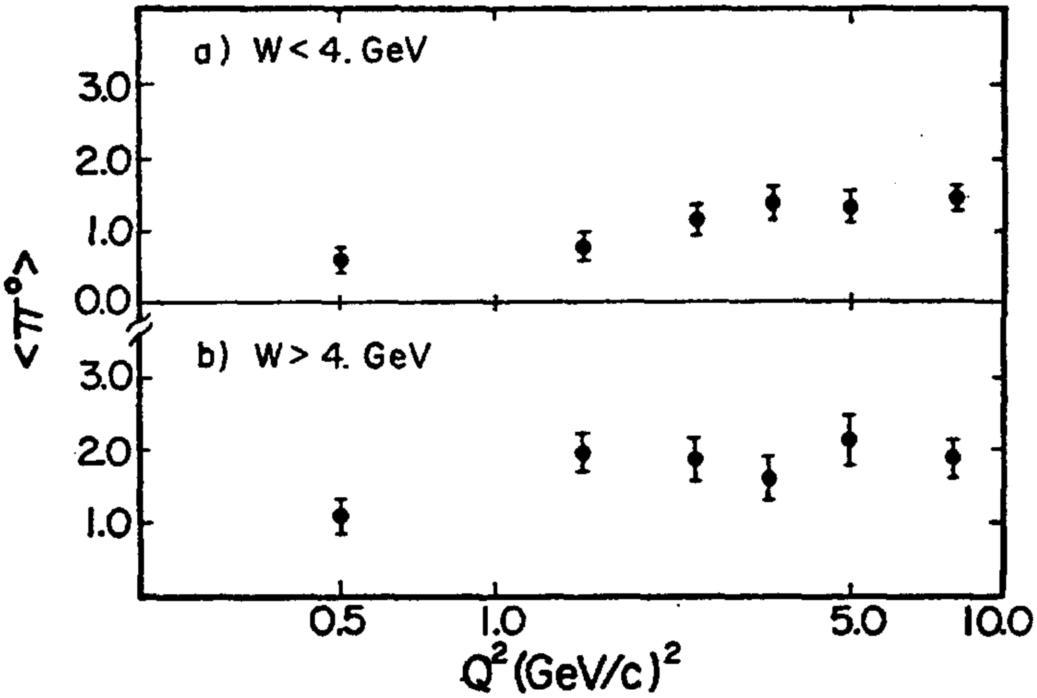

Fig. 5. The average number of π^0's as a function of Q^2 for two regions of W.

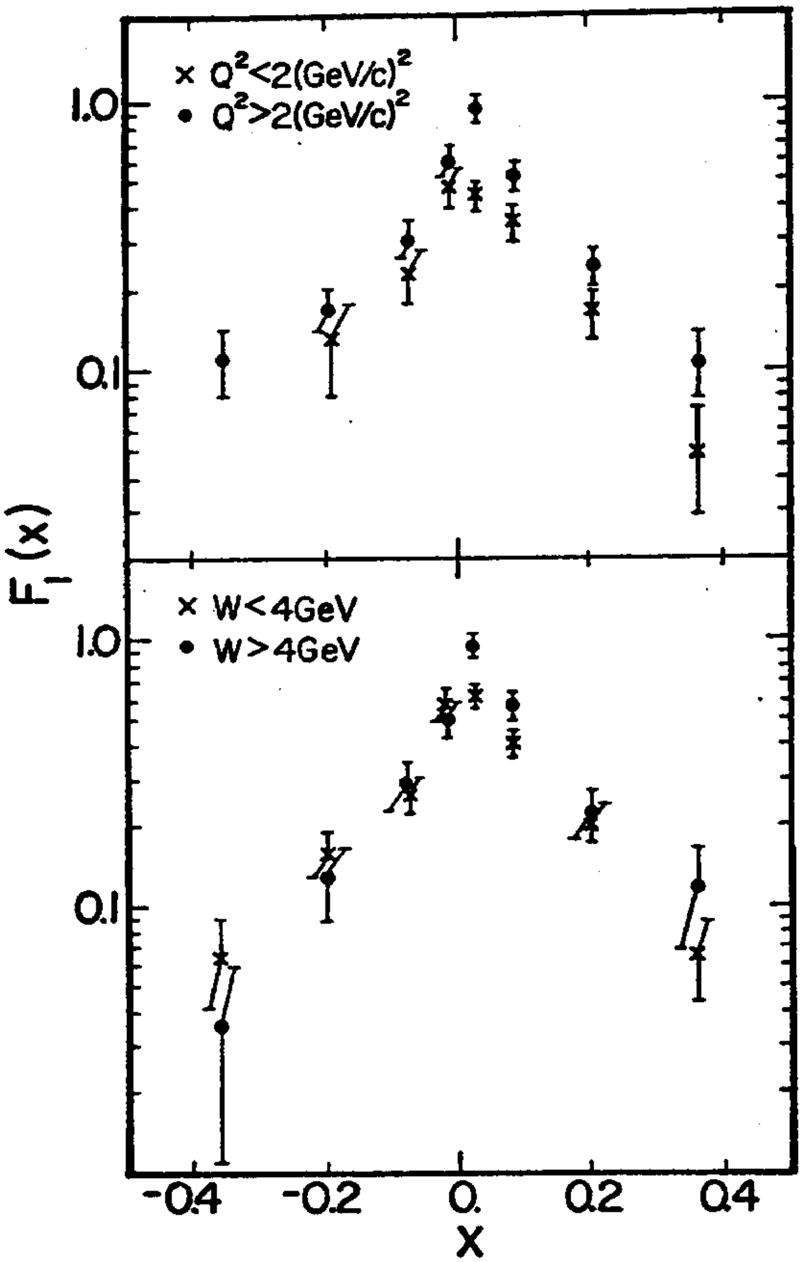

Fig. 6. Invariant γ cross sections $F_1(x)$: (a) for two regions of Q^2 and (b) for two regions of W.

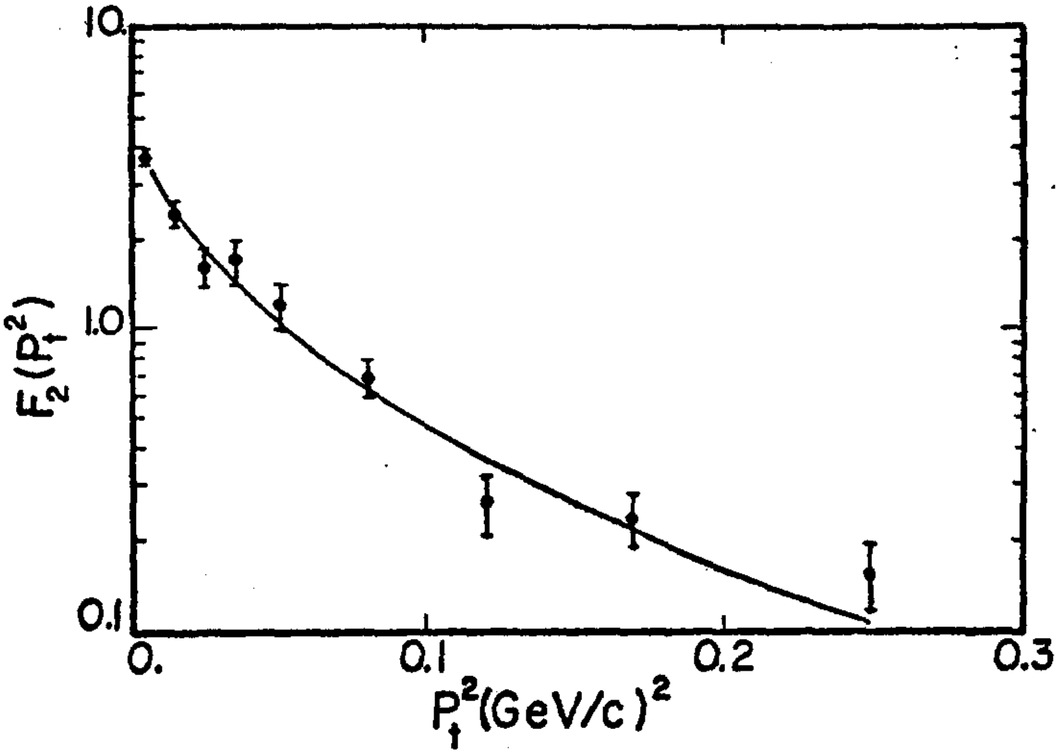

Fig. 7. Invariant γ cross section $F_2(P_t^2)$. The solid line is a fit of the form $P_t^{-1} \exp(-P_t^2/B)$.

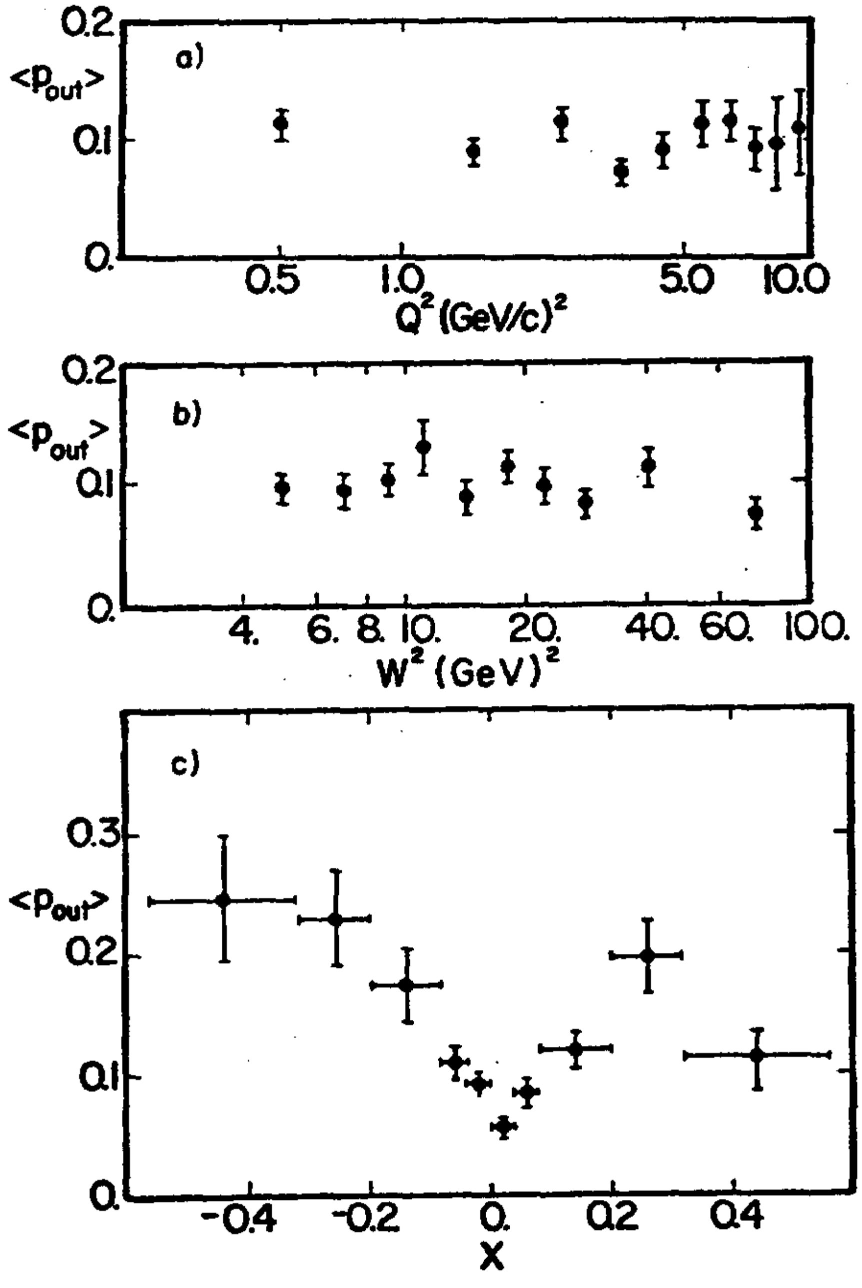

Fig. 8. The mean value of $< P_{out} >$ as a function of Q^2, W^2 and x are shown in (a), (b), and (c) respectively.

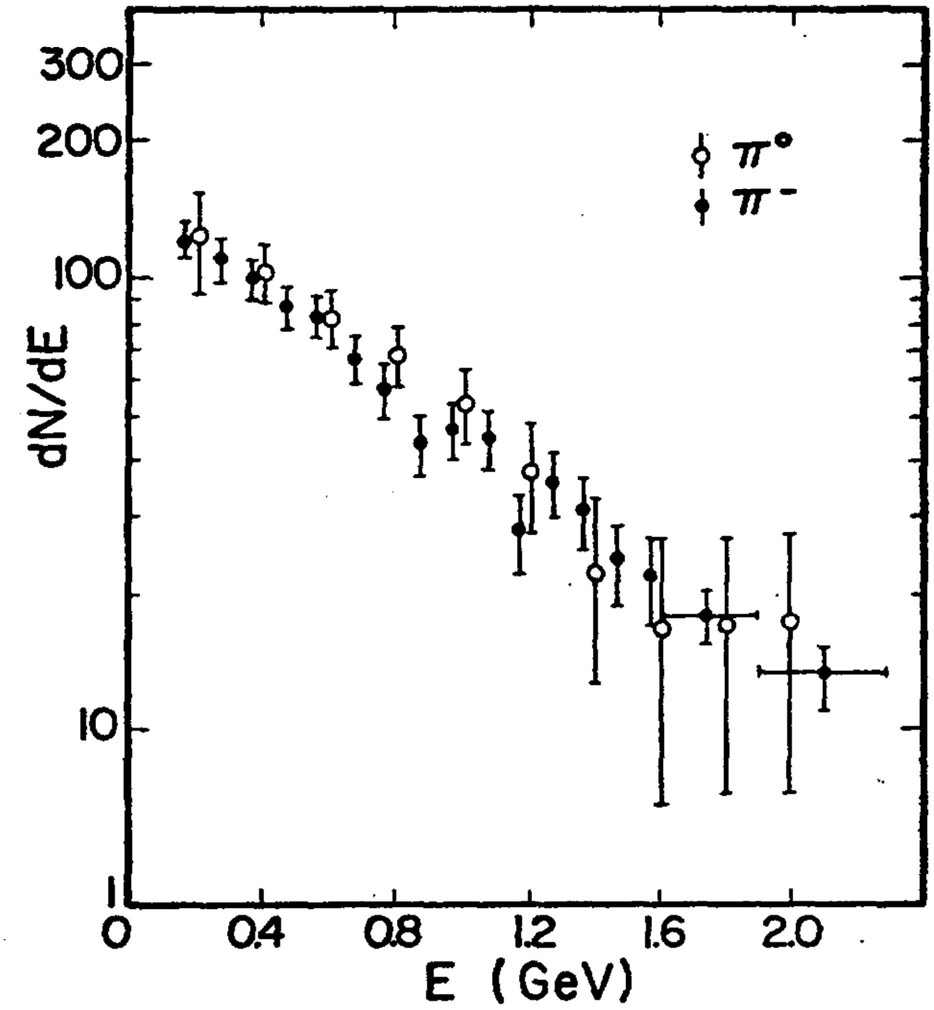

Fig. 9. The π^0 and π^- energy spectrum.

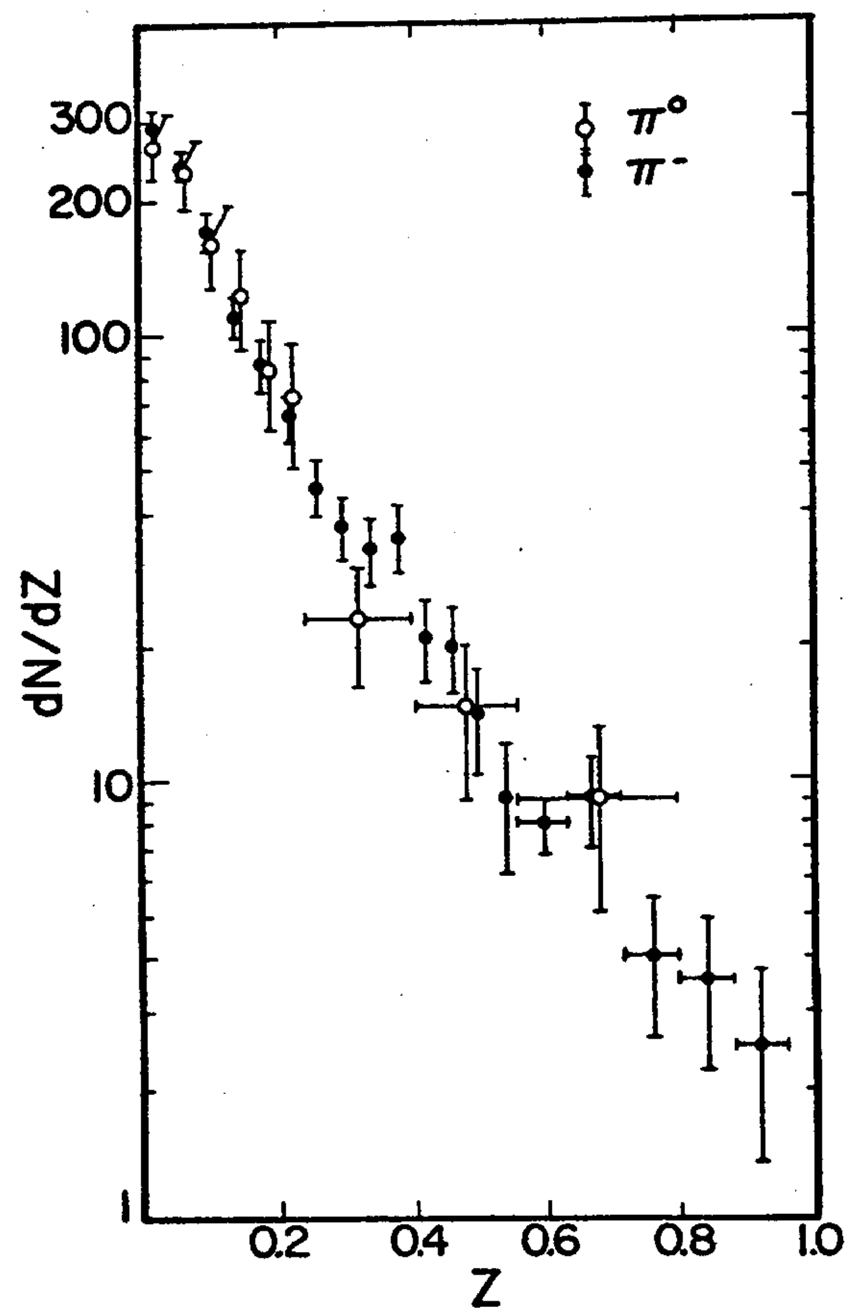

Fig. 10. The number of π^0 and π^- as a function of Z.