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FURTHER MEASUREMENT OF NUCLEON STRUCTURE FUNCTION IN HIGH ENERGY MUON-IRON INTERACTIONS

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ABSTRACT

We present a further measurement of the nucleon structure function F_2 for $6 < q^2 < 130\ (\mathrm{GeV}/c)^2$ and $0.045 < x < 0.55$. Values of structure functions are presented in the kinematical variables q^2, x, and also ν. The data are in qualitative agreement with the neutrino scattering data in a large kinematical range of overlap. A fit of the data to the perturbative QCD model of Abbott and Barnett was made. Experimental and theoretical uncertainties in the fits to F_2 are discussed.

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In a previous Letter[1] we reported an early measurement of the nucleon structure function for deep inelastic muon scattering, F_2, as a function of our momentum transfer squared q^2 for several bands of $x = q^2/2m\nu$, where ν is the energy transfer, $E_\mu - E_{\mu'}$; $q^2 = 2E_\mu E_{\mu'}(1-\cos\theta_\mu)$, θ_μ is the scattering angle and M is the nucleon mass. While the results confirmed the scaling violation observed in an earlier work[2], at higher q^2, the data were not easily accounted for by the simple QCD fit[3] obtained with the SLAC-MIT ed data. To study this question further, we present here an additional measurement of F_2, based on a three fold increase in event statistics and an increased kinematical range. The entire data set is then fit using an improved perturbative QCD procedure.

The experimental apparatus and the method of analysis were described earlier[1,4]. Briefly, a momentum analyzed beam of positive muons at the Fermi National Accelerator Laboratory impinged on an iron/scintillator sandwich ionization calorimeter (target detector) in which the muon interaction occured, and in which the final-state hadron energy E_h was measured. The vector momentum of the scattered muon $E_{\mu'}$ was determined in a toroidal magnetic spectrometer directly downstream of the target calorimeter. The scattering angle was determined with proportional chambers before and after the target. The incident (scattered) muon energy $E_\mu(E_{\mu'})$ was measured to 1.5 (9)%. Data were collected with the muon energy set at 270 GeV, generated in proton-nucleus collisions for proton energy E_p of 400 GeV.

Muon interactions were selected within a fiducial region of the target calorimeter, of cross-sectional area 0.5 x 0.5 m^2, length along the muon beam 7.38 m, and total thickness 4250 g/cm^2. Any event with $q^2 \leq 6(GeV/c)^2$ and $\nu < 20$ GeV was not included in the analysis because of the small value of the apparatus acceptance. The minimum value of the invariant hadron mass W^2_{min} was 40 GeV^2 for this experiment. The maximum values for q^2, ν, and W^2 were 120 $(GeV/c)^2$, 210 GeV and 370 GeV^2 respectively. The combined cut on q^2 and ν yielded 3.8 x 10^5 muon-iron interactions, defining the kinematical range 0.045 - 0.55 in the scaling variable x.

The values of the nucleon structure functions were extracted from the data by making a direct comparison of the measured distributions with a Monte Carlo simulation which takes into account the apparatus acceptance and its resolution. The effects which induced a finite resolution, such as multiple Coulomb scattering, nuclear Fermi motion of the nucleon in iron nuclei, straggling effects in the target and the spectrometer, and

finite measurement errors in the spectrometer were considered. Radiative corrections, wide-angle bremsstrahlung, and muon flux corrections, all of which affect the absolute normalization of the data, were taken into account. The kinematic variables q^2 and x are referenced to "true" values using correlations between true and reconstructed values from the Monte-Carlo program.

We show in fig. 1 values of F_2 in the scaling variable x for eight bands of energy transfer, ν. This plot particularly favours a comparison with the corresponding values of F_2 obtained in a neutrino-iron scattering experiment[5] (x 5/18 as given by the quark-parton model) and the electron-deuteron scattering (x 1/2) of the SLAC-MIT Collaboration[6]. Good qualitative agreement between these experiments is evident. The overall agreement is within 10%.

The shape of observed $F_2(x)$ is shown for nine bands of q^2 in fig. 2. A pronounced peaking at small x (< 0.2) is evident. The measured values of F_2 depend on the values of $R(\equiv \sigma_L/\sigma_T)$ in the cross section formula:

$$\frac{d^2\sigma}{dE_{\mu'}d\theta} = \frac{8\pi\alpha^2 E_{\mu'}\sin\theta\,\cos^2\frac{\theta}{2}}{(q^2)^2\,y} F_2(x,q^2)\left\{1 - y + \frac{Mxy}{\nu}\left(\frac{1+\nu^2q^2}{1+R}\right)\right\}$$

In fig. 2 the closed circles show the values of F_2 where R is assumed to be the QCD form[7] $R = R_0(1-x)/q^2$, where R_0 is $1.2 \pm {}^{0.43}_{0.36}$. As all available data on R can be fitted by a constant, we also derived F_2 with R = 0.25, shown by a cross in the figure. The effect of varying R in this way increased F_2 by a few percent at small $y(\equiv \nu/E_{\mu'})$ to about 12% at large y. A general analysis of separating F_2 and R was not performed, owing to the requirement of measuring F_2 at fixed values of q^2 and ν for different incident muon energies.

The $F_2(q^2)$ for seven x bands from 0.045 to 0.55 is shown in fig. 3. The central value of the x-bins were chosen in conformity with other deep inelastic muon and neutrino scattering experiments. The lower-q^2 range of the data appear to join up smoothly with the MIT-SLAC data. At higher q^2, the data exhibit a flattening trend.

It is of particular interest to examine to what extent the scale non-invariance of F_2, first made evident in muon scattering[2], corresponds to the prediction of quantum chromodynamics (QCD), recently proposed as the theory of the strong interaction. In QCD the scale parameter Λ charac-

terizes the strength of the scaling violations and is related to the effective gluon coupling constant $\alpha_s(q^2) = 4\pi/\left\{(11 - \frac{2}{3} n) \ln\frac{q^2}{\Lambda^2}\right\}$ where n is the number of quark flavors. By choosing the form of $F_2(x, q^2)$ at some $q^2 = q_0^2$, the evolution equations in QCD give the resultant F_2 at all q^2. A comparison can then be made with the experimental data. To fit our data to the QCD predictions, we adopted a procedure of Abbott and Barnett[8]. The fitting parameters, such as Λ and the k_i in the equation $F_2(x,q_0^2) = k_1(1-x)^{k_2}(1+k_3)$ were simultaneously adjusted until the best fit was obtained. The procedure ensured that the rapidly varying x-dependence of F_2 was also accounted for at all q^2 rather than predetermined[3] at a fixed q^2. Furthermore, the power P_G in the gluon distribution was also adjusted. We performed the fits without taking into account of target mass effects, higher order corrections[9], and higher twist effects[8]. To help avoid these theoretical difficulties, only data with $q^2 \geq 3$ $(\mathrm{GeV}/c)^2$ were used in the final analysis. Even so, the values of Λ thus obtained still depended on the input data sample. The solid curves in fig. 4 show a fit to our data, combined with the SLAC-MIT data, for $\Lambda = 0.5 \pm 0.2$ GeV, $k_1 = 1.52 \pm 0.20$, $k_2 = 1.58 \pm 0.20$, $k_3 = 0.8 \pm 0.5$ and $P_G = 1.0 \pm 0.5$. Fitting our data alone yields a lower Λ value of 0.10 ± 0.05 GeV, shown by the dashed curve. The errors depend mainly on the relative normalization of the two experiments and the estimated systematic errors. The chi-squared of these fits is about one per degree of freedom. Since we expect some target-mass and higher-twist corrections in the regime of the SLAC-MIT data, especially for $q^2(1-x) \lesssim$ a few GeV^2, the effective Λ should lie between $0.1 < \Lambda < 0.5$, depending again on the assumptions made in the QCD model.

Other factors must also be considered in a test of QCD. The dimuon events observed[4,11] in deep inelastic muon scattering were interpreted as being due to the associated production of charm mesons ($\mu N \rightarrow \mu D\bar{D}X$) at small values of x[10-12]. The magnitude of the observed charm cross section[4] is such that a significant portion of the observed scaling violations might be due to charm production[13]. An account of the charm contribution at small x from F_2 may alter the range for Λ further.

If one assumes $\Lambda \approx 0.5$ GeV, one finds a small variation of F_2 ($\sim 10\%$) around the fit[14] for a small region of W^2, as originally discussed in our previous Letter[1]. This variation, being at the limit of systematic uncertainty, may well be artificial, although it cannot yet be totally ruled out[15]. However, this variation appears reduced if we accept the smaller

values[16] of Λ than we previously assumed.

We summarize these results as follows. The nucleon structure function in muon scattering has been measured over a large kinematical range. Agreement is seen when comparing the data with the neutrino data which are appropriately normalized assuming the validity of the quark-parton model. Little difference (to $\sim$ 10% level) is seen when probing the nucleon structure with different leptonic projectiles. The behavior of F_2 can be qualitatively explained by quantum chromodynamics with a scale parameter ranging from 0.1 to 0.5 GeV. Although our data favor the lower value of Λ, the scale parameter cannot be unambiguosly established, partly because of the theoretical uncertainty on the effects of target-mass and higher-twist corrections and partly because of the experimental uncertainty on the values of R, as well as possible effects of charm threshold at small x. The support of QCD using deep inelastic muon data in this q^2 range should not yet be viewed as definitive.

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14. In general, these comparison are model and normalization dependent. Comparing with the fit with $\Lambda = 0.5$, F_2 is plateaued at ~ 0.95 below $W^2 \sim 85$ GeV^2, rising to ~ 1.05 for $W^2 \sim 180$ GeV^2. The low points could be due to some target mass or high twist effects not discussed here.

15. Other unpublished high-q^2 muon scattering data also cannot rule out a 10% variation in F_2 due to systematic errors and model dependence of fits to F_2. A precise $\sqrt{s}$ dependence of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ may well be the best way to study this problem.

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FIGURE CAPTIONS

Fig. 1 Nucleon structure function F_2 as a function of x for different ranges of the virtual photon energy ($\nu = E_\mu - E_\mu'$), shown in closed circles. Open circles (o) represent values of $F_2^{\nu N}$ x 5/18 from ref. 5. Open triangles (Δ) represent values of F_2^{ed} x 1/2 of ref. 6 a) $10 < \nu < 20$; b) $20 < \nu < 30$; c) $30 < \nu < 50$; d) $50 < \nu < 75$; e) $75 < \nu < 100$; f) $100 < \nu < 150$; g) $150 < \nu < 200$; h) $\nu > 200$ GeV. The errors shown are statistical only.

Fig. 2 F_2 plotted against x for seven bands of q^2: a) $10 < q^2 < 15$, b) $15 < q^2 < 20$; c) $20 < q^2 < 25$; d) $25 < q^2 < 30$; e) $30 < q^2 < 40$; f) $40 < q^2 < 50$; g) $50 < q^2 < 80$; h) $80 < q^2 < 120$; i) $120 < q^2 < 200$ (GeV/c) . Open circles are $F_2^{\nu N}$ x 5/18 and open triagles are F_2^{ed} x 1/2 respectively. F_2 shown in closed circles are obtained with $R(\equiv \sigma_L/\sigma_T) = \frac{1.2(1-x)}{q^2}$. For R = 0.25, F_2 are shown in a cross (+). The errors shown are statistical only.

Fig. 3 F_2 versus q^2 for different bands of x in a linear-linear scale (closed circles). Shown also are $F_2^{\nu N}$ x 5/18 (open circles) and F_2^{ed} x 1/2 (open triangles); a) $0.03 < x < 0.06$; b) $0.06 < x < 0.10$; c) $0.1 < x < 0.2$; d) $0.2 < x < 0.3$; e) $0.3 < x < 0.4$; f) $0.4 < x < 0.5$; g) $0.5 < x < 0.7$. The errors shown are statistical only.

Fig. 4 Values of $\ln F_2$ as a function of $\ln q^2$ for seven bands of x (closed points). Open circles are the F_2^{ed} x 1/2 of the SLAC-MIT Collaboration (ref. 6). The values of x are given on the right. Two perturbative QCD fits are shown: solid lines are fits to the combined data with Λ = 0.5 GeV and dashed lines, Λ = 0.1 GeV without the data of ref. 6. The nature and values of adjustable parameters in the fit are discussed in the text.

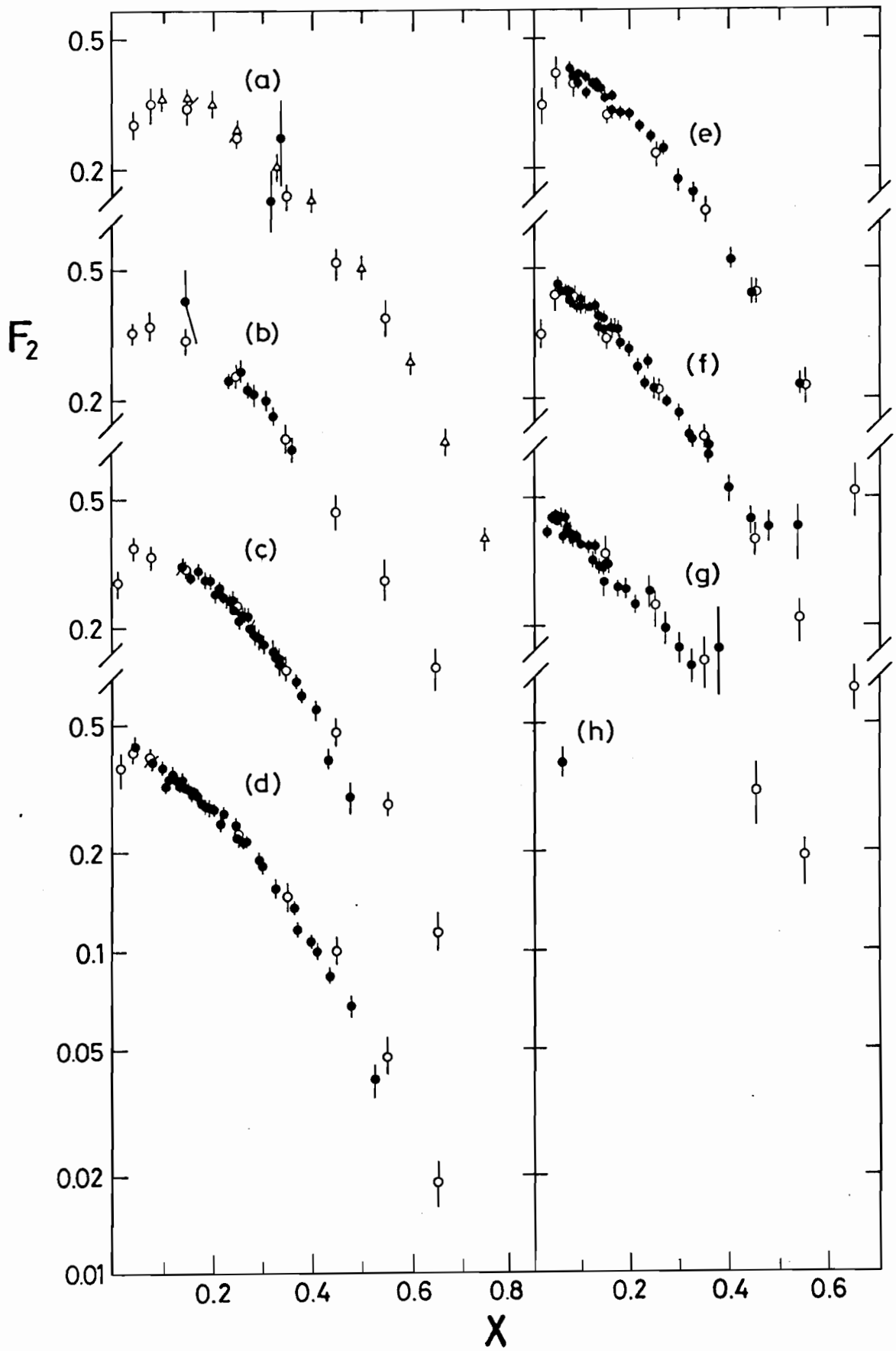

Figure 1

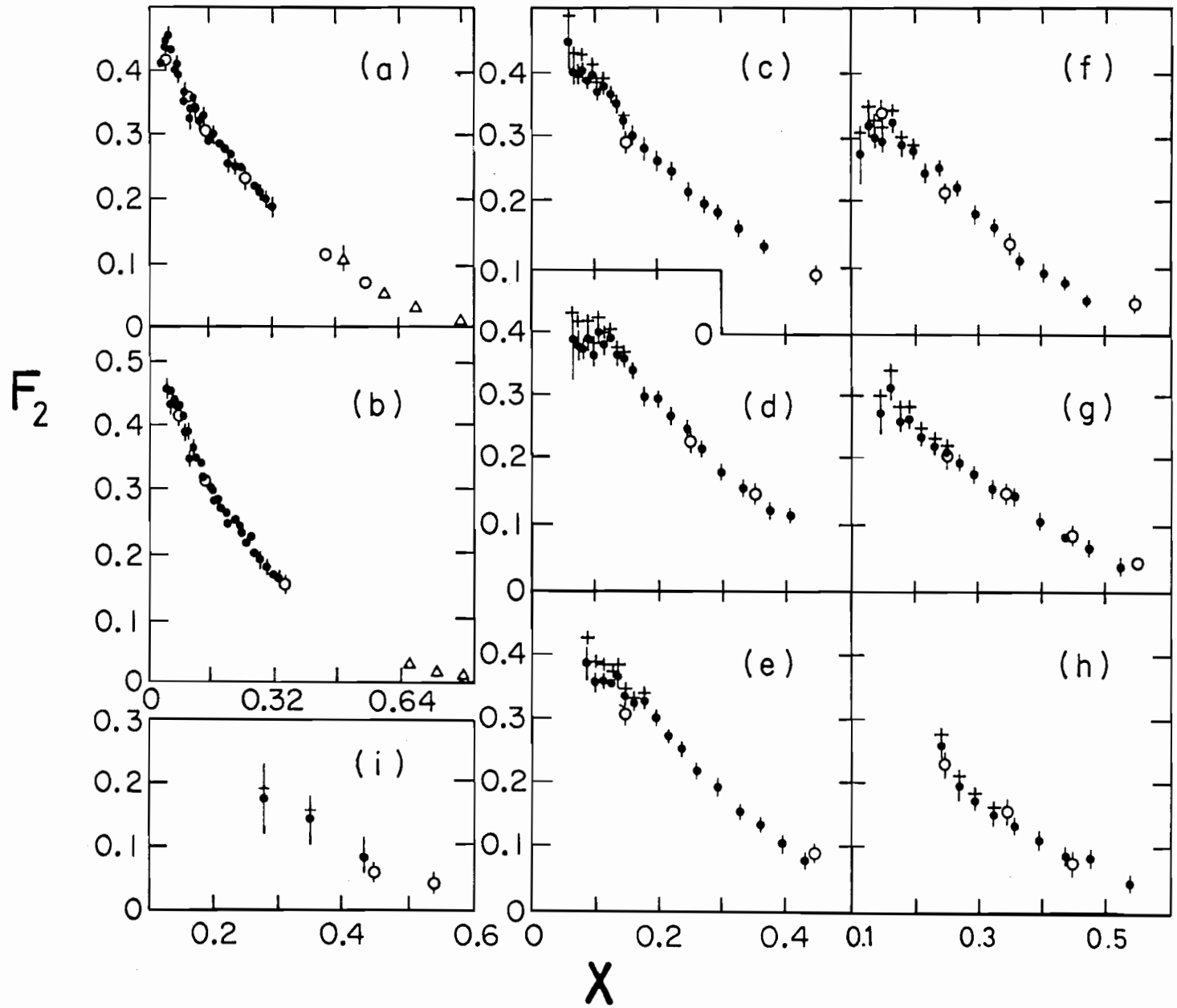

Figure 2

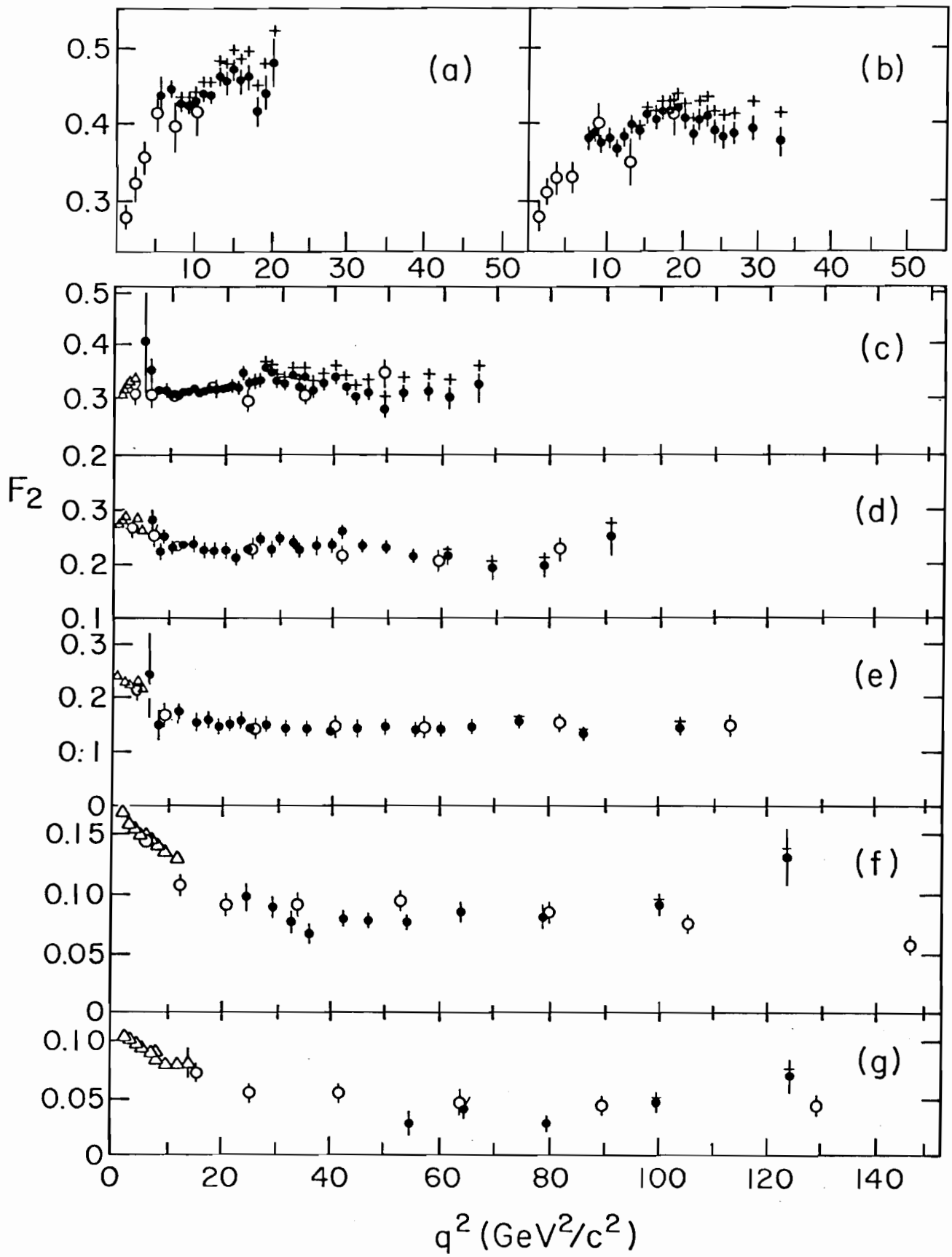

Figure 3

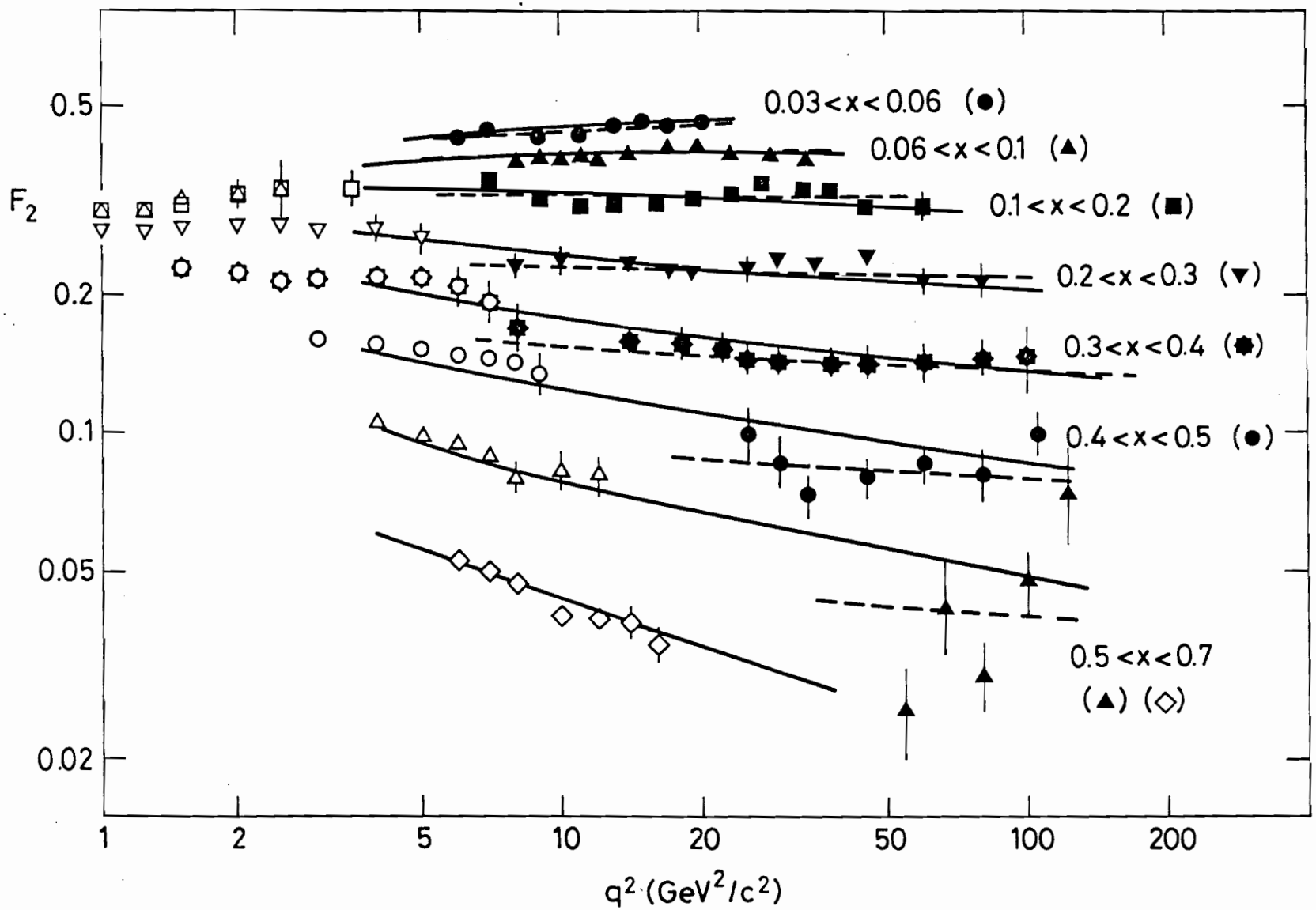
0.03<x<0.06 (●)
0.06<x<0.1 (▲)
0.1<x<0.2 (■)
0.2<x<0.3 (▼)
0.3<x<0.4 (✱)
0.4<x<0.5 (●)
0.5<x<0.7
(▲) (◇)
F2
0.5
0.2
0.1
0.05
0.02
1
2
5
10
20
50
100
200
q2 (GeV2/c2)

Figure 4