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Abstract: *Regge behaviour of the proton structure functions as a function of the squared missing mass W^2 at fixed values of Q^2 is investigated and compared with the data from HERA and NMC. The relevant kinematical boundaries and the relative importance of various Regge pole trajectories are also discussed.*

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A prominent feature of the small-x behaviour of the structure functions, as revealed from HERA, is their Regge behaviour. For small enough x, one can approximate $x \sim 1/s$, where s is the usual Mandelstam variable, and (see, e.g. [1])

$$F_2(x) \sim \left(\frac{1}{x}\right)^{\alpha-1} \sim s^{\alpha-1}. \tag{1}$$

where $\alpha \equiv \alpha(0)$ is the intercept of the relevant Regge trajectory. Small x and fixed Q^2 data can be described quite satisfactory by a single "supercritical" pomeron, $\alpha > 1$. At the same time, applications of the Regge pole picture to deep inelastic scattering raised new problems, and above all - the Q^2- dependence of the pomeron intercept, as it appears from straightforward fits (see e.g.[2]) to the data. The observed variation of the intercept raised speculations about the possible existence of two different pomerons - a "soft" (small Q^2) and a "hard" (large Q^2) one.

One reason for confusion may be that while the data are exposed and analyzed in the variables x and Q^2, the proper energy variable in which the Regge pole approach is expected to be efficient is the squared missing mass W^2 (at least at large values of W^2). The present paper is the first step towards a Regge pole analysis of the data in the above kinematical variable.

The relevant kinematics is shown in Fig.1, with the standard notations:

$$\begin{aligned}
&k^2 = k'^2 \simeq 0, \\
&q = k - k', \qquad Q^2 = -q^2, \\
&\nu = pq, \qquad x = Q^2/2\nu, \\
&s = (p+q)^2 = Q^2(1/x - 1) + W^2.
\end{aligned}$$

The necessary conditions for the Regge asymptotic behaviour to hold are:

1) the interaction energy must be sufficiently large to produce many particles in the final state

$$W^2 \gg m^2,$$

where m is a typical hadronic mass (Fig.2). As far as $W^2 = Q^2(1/x - 1) + m^2$ one can obtain at x not closed to 1

$$Q^2/m^2 \gg x;$$

2) the cosine of scattering angle in t-channel (see Fig.2) is large. In deep inelastic scattering one has $t = 0$, hence

$$z = |\cos\theta_t| = \frac{W^2 + Q^2 - m^2}{2\sqrt{Q^2 m^2}} \gg 1,$$

and thus

$$Q^2/m^2 \gg x^2.$$

The first condition is the stronger one if $x \neq 1$. Hence , Regge behaviour is expected in the region

$$Q^2 \geq \frac{x}{1-x}(W^2_{min} - m^2)$$

In what follows we will set $W_{min} = 3GeV$.

The sum of the longitudinally and transversely polarized virtual photon-proton cross-sections is

$$\sigma_L + \sigma_T = \frac{4\pi^2\alpha(1+4m^2x^2/Q^2)}{Q^2(1-x)} F_2(x,Q^2) \tag{2}$$

The ratio $R = \sigma_L/\sigma_T$ is small and usually it is neglected. (Recent small x data [7b,d] indicate that this is not neccessarely justified.)

Following the original paper [3],[4] (see also [2]), and in analogy with hadronic processes, we assume that the total cross-section

$$\sigma = \sigma_L + \sigma_T = ImA(W^2, t=0, Q^2) \tag{3}$$

is Regge behaved in the domain specified above. In γp scattering, by quantum number conservation, only positive C-parity exchange is allowed. We include the leading pomeron and the f-meson contributions. The exchange of the A_2-reggeon is neglected for the sake of simplicity. It may affect the small W^2 and/or large x behaviour of the cross section.

Thus we write

$$A = \mathcal{P} + f, \tag{4}$$

where P and f stand for the pomeron and f-exchanges. They are parametrized as

$$f = g_f(1-x)^{b_f} R_f(Q^2)(W^2/m^2)^{\alpha_f(0)-1} \tag{5}$$

and

$$\mathcal{P} = \mathcal{P}_1 + \mathcal{P}_2 \tag{6}$$

with

$$\mathcal{P}_1 = g_1(1-x)^{b_1} R_1(Q^2)\log(W^2/m^2), \tag{7}$$

$$\mathcal{P}_2 = g_2(1-x)^{b_2} R_2(Q^2). \tag{8}$$

The choice of the "residua functions" $R(Q^2)$ is based on the observation that the structure functions have a power-like decrease in Q^2. It can be seen from Fig.3 that this power is approximately equal to one and it weakly depends on Q^2. Therefore we have used a simple parametrization

$$R_i(Q^2) = \frac{1}{(1+Q^2/Q_i^2)^{r_i(Q^2)}} \tag{9}$$

with

$$r_i(Q^2) = r_i\Big(1 + \frac{d_i}{1+Q^2/Q_i^2}\Big), \qquad r_i = const. \tag{10}$$

The restriction $r_2 \geq r_1$ is required (if $g_2 < 0$ (see Table)) by the positivity of the cross-sections at fixed W and $Q^2 \to \infty$. Note that the resulting fits with $d_i \neq 0$ are much better than those with $d_i = 0$.

The choice (6) - (8) corresponds to a particular model for the pomeron, known as the dipole pomeron (see [5] and earlier references therein). It realizes a moderate rise of the total cross-sections and, similar to a "supercritical" pomeron with $\alpha(0) - 1 \leq 0.1$ [2b-2e],

yields good fits to the data on hadronic cross-sections. Note that this model has a minimal number of free parameters and does not saturate the Froissart bound.

The parameters g_1, g_2 and g_f were determined from a fit to the real photon-proton cross-section at $W \geq 3GeV$

$$\sigma_{\gamma p} = g_1 \log(W^2/m^2) + g_2 + g_f (W^2/m^2)^{\alpha_f(0)-1}.$$

The value of the f-trajectory intercept, $\alpha_f(0) \simeq 0.8$ was taken from our earlier fits [6] to total cross-section data made within the dipole pomeron model. This value may change somewhat if the A_2 exchange is included and/or other models for the pomeron are used.

Expression (2) with (6)-(10) was fitted to the data on structure functions from H1, ZEUS, and NMC [7]. A total of 317 data points for $Q^2 \neq 0$ limited by $x \leq 0.35$ were involved in the minimization procedure. The results of the best fit ($\chi^2/number\ of\ points = 1.03$) are shown in figs. 4.a-4.d with the values of the fitted parameters given in Table **1**.

Our first conclusion is that deep inelastic cross-sections are Regge behaved in a much wider kinematical range than previousely assumed. There is no evidence from the experimental data for a violation of the Froissart bound. Nonleading contributions to the cross-section in the kinematical region under consideration are non-negligable. Analysis of the model with parameters given in the Table shows that the region where the f-reggeon dominates expands in W^2 as Q^2 increases (for example, at $Q^2 = 50GeV^2$ the ratio of partial contributions $\sigma_f/\sigma_{\mathcal{P}}$ is small at $W \geq 10GeV$, but at $Q^2 = 5000GeV^2$ this ratio is small in the region $W \geq 80GeV$) . The similar conclusion may be true for the A_2-reggeon contribution.

Another important conclusion that follows from our analysis is that the pomeron is a unique object; a single Regge singularity - the pomeron (plus a secondary reggeon) fits the data in a wide kinematical region and there is no need for a multitude of different ("soft", "hard", etc.) pomerons. In our opinion, the introduction of two or many pomerons does not only lead to the proliferation of the free parameters but it is also conceptually misleading (see also [8] for a discussion of this point).

We are aware that by factorization, the reggeon (pomeron) intercept should be Q^2-independent. However, its variation with Q^2 may only indicate that: 1) the pomeron is a more complicated singularity than just a simple pole, used here to replace effectively a complicated object including contributions from unitarity corrections (difficult to calculate unambiguously); 2) as it follows from our analysis, the asymptotic regime, dominated by a pomeron exchange, has not yet been uniformely achieved.

In this paper, for simplicity, we have used a particular model for the pomeron, defined by eqs.(6)-(10). We expect that our conclusion concerning the uniqueness of the pomeron will hold also for other models (supercritical pomeron, Froissaron, etc.). Relevant fits will be presented in a forthcoming publication.

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Table 1. Values of the parameters obtained from a fit to the experimental data [7].

Pomeron contributions		f-reggeon contribution	
$g_1 = 0.0177mb$	$g_2 = -0.0572mb$	$\alpha_f(0) = 0.8$	$g_f = 0.226mb$
$Q_1^2 = 2.774GeV^2$	$Q_2^2 = 6.568GeV^2$		$Q_f^2 = 0.466GeV^2$
$r_1 = 1.098$	$r_2 = 1.098$		$r_f = 0.947$
$d_1 = 0.928$	$d_2 = 1.192$		$d_f = 0.099$
$b_1 = 12.993$	$b_2 = 16.698$		$b_f = 0.780$

Figure captions

Fig1. Diagram for a process of deep inelastic scattering.

Fig2. "Optical theorem" for a virtual photon-proton interaction.

Fig3. Experimental data (from [7]) for the cross-section rewritten as function of Q^2 and combined in groups with various intervals in W.

Fig4.,a-d. Fitted cross sections σ at different values of Q^2 in the model (4)-(10) with parameters given in the Table.

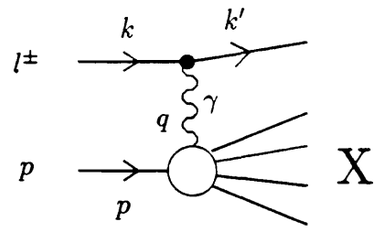

Fig.1

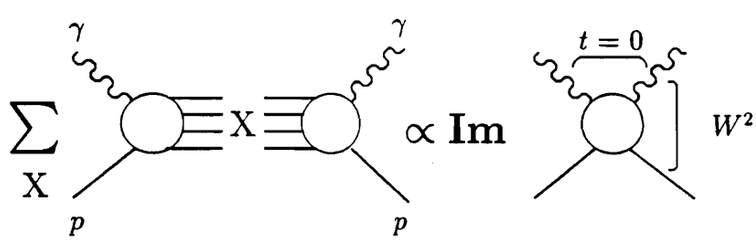

Fig.2

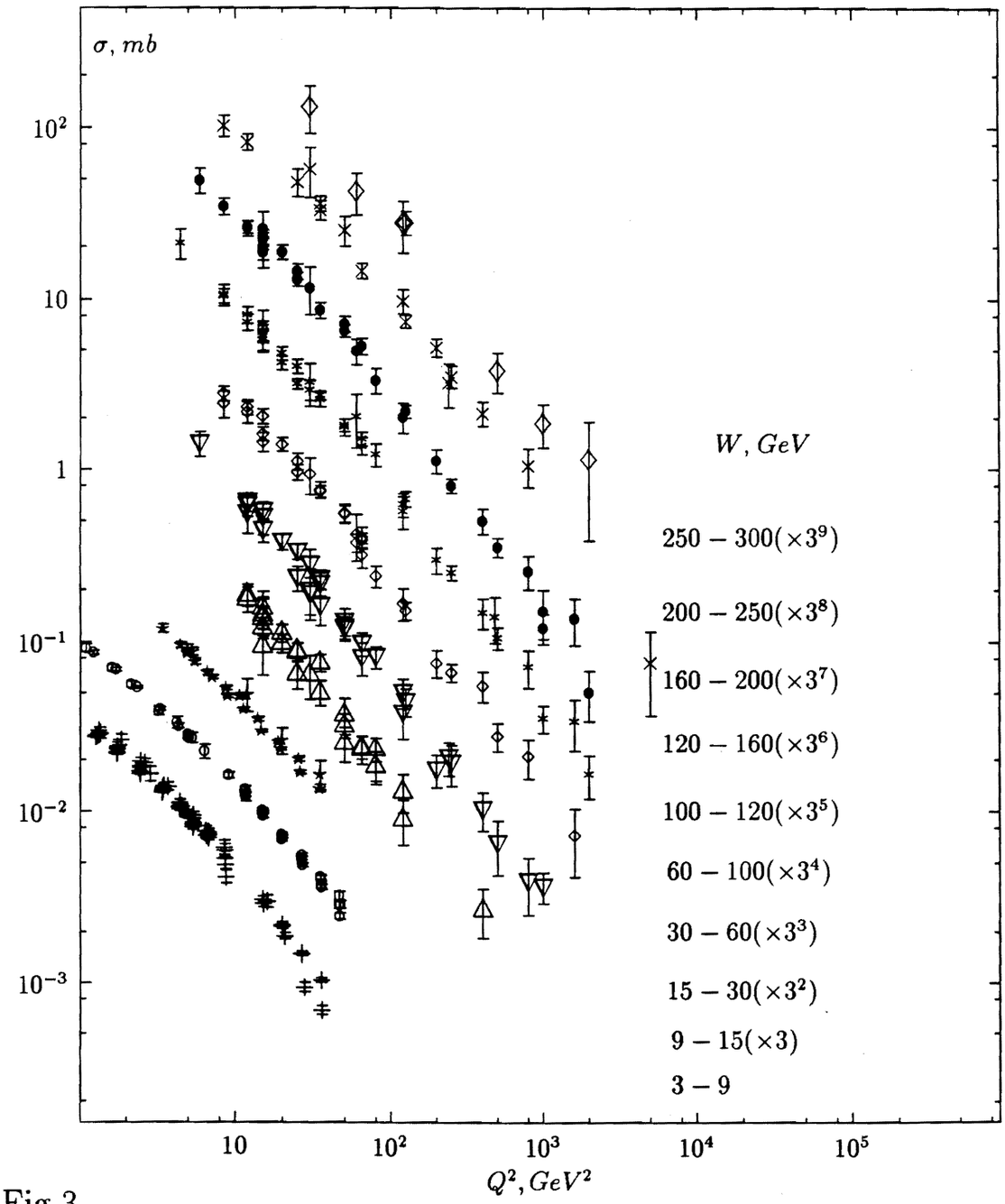
σ, mb
10²
10
1
10⁻¹
10⁻²
10⁻³
10
10²
10³
10⁴
10⁵
Q², GeV²
W, GeV
250 − 300(×3⁹)
200 − 250(×3⁸)
160 − 200(×3⁷)
120 − 160(×3⁶)
100 − 120(×3⁵)
60 − 100(×3⁴)
30 − 60(×3³)
15 − 30(×3²)
9 − 15(×3)
3 − 9

Fig.3

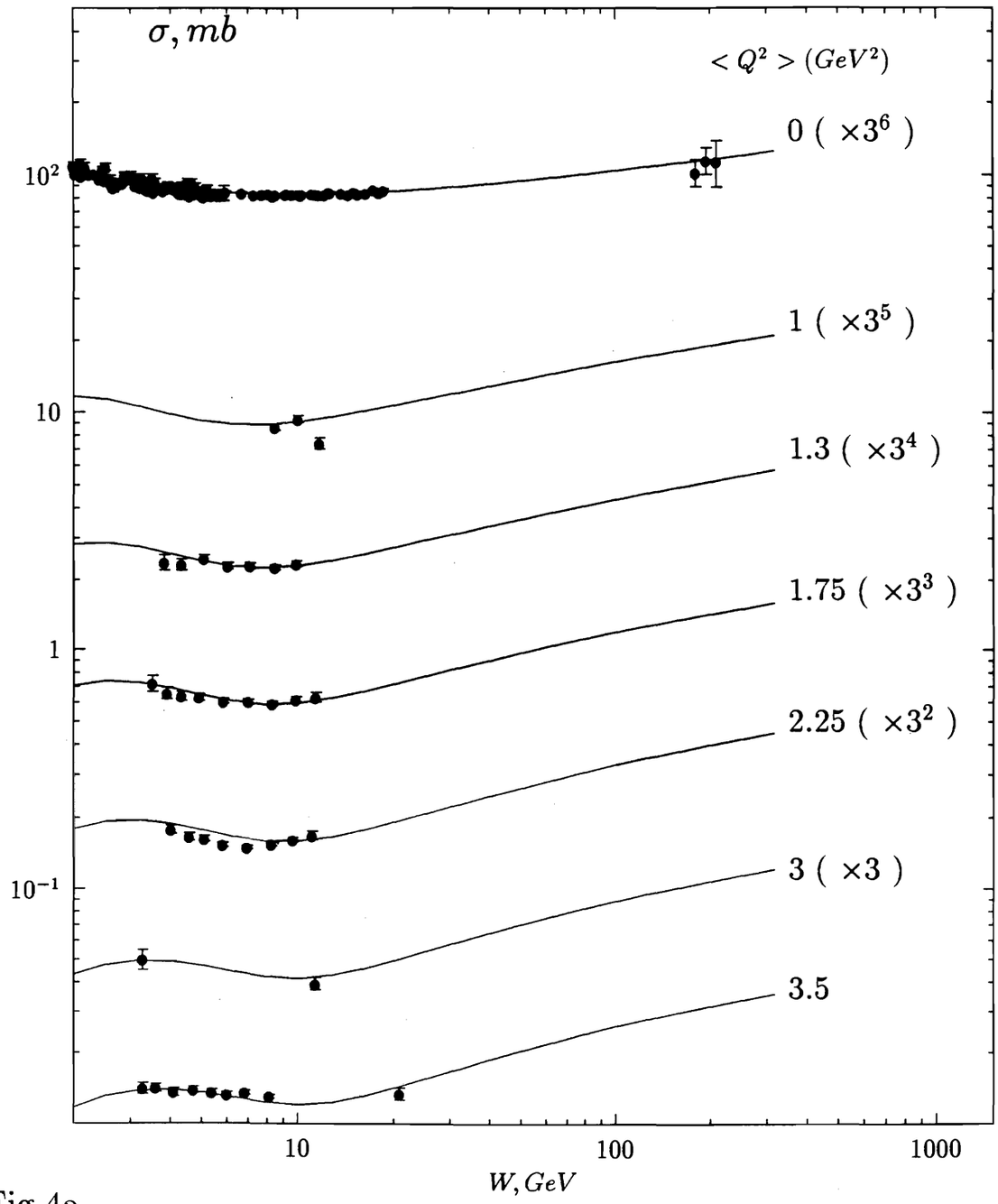
σ, mb
< Q² > (GeV²)
0 (×3⁶)
1 (×3⁵)
1.3 (×3⁴)
1.75 (×3³)
2.25 (×3²)
3 (×3)
3.5
10²
10
1
10⁻¹
10
100
1000
W, GeV

Fig.4a

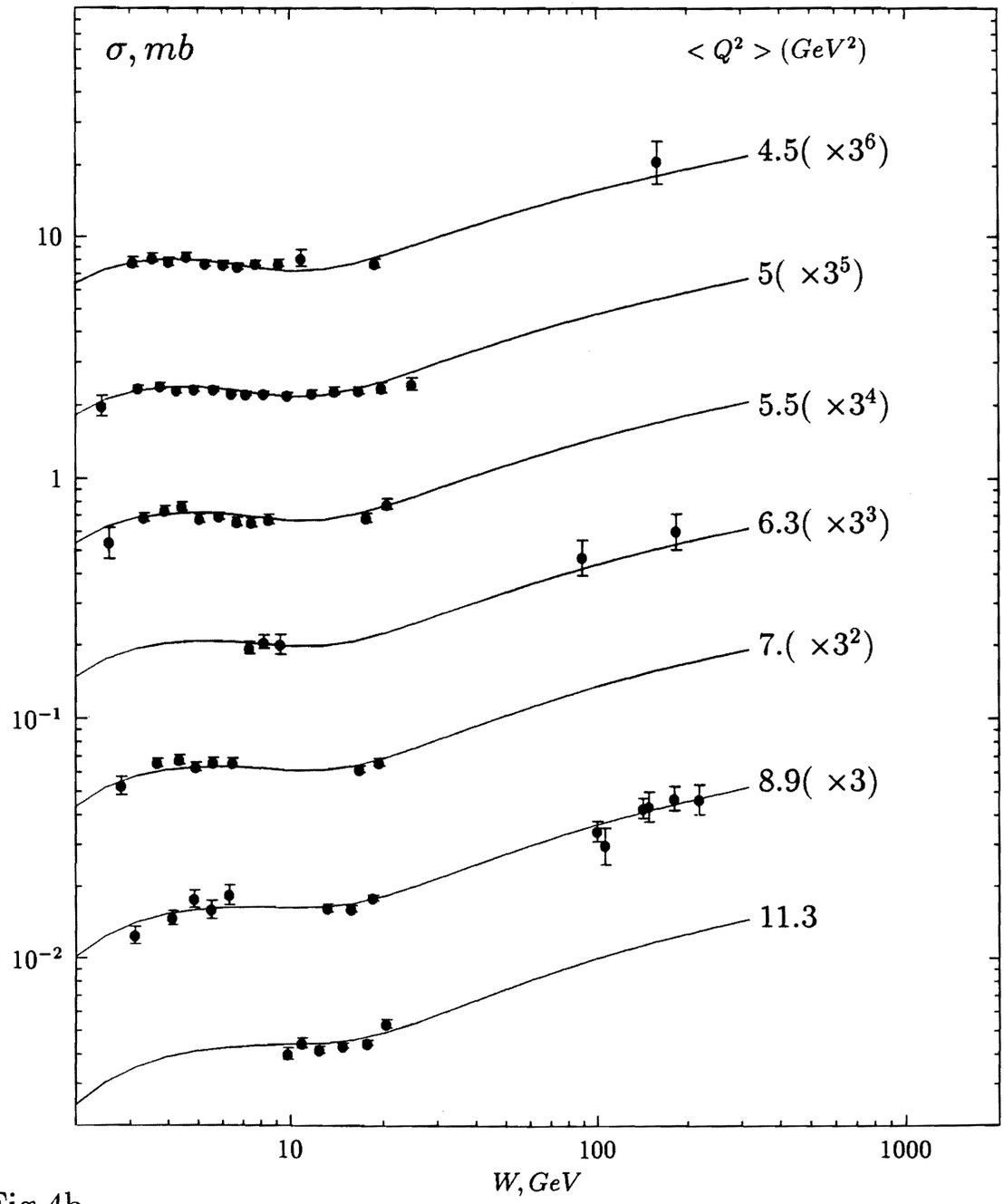
σ, mb
< Q² > (GeV²)
4.5(×3⁶)
5(×3⁵)
5.5(×3⁴)
6.3(×3³)
7.(×3²)
8.9(×3)
11.3
10
1
10⁻¹
10⁻²
10
100
1000
W, GeV

Fig.4b

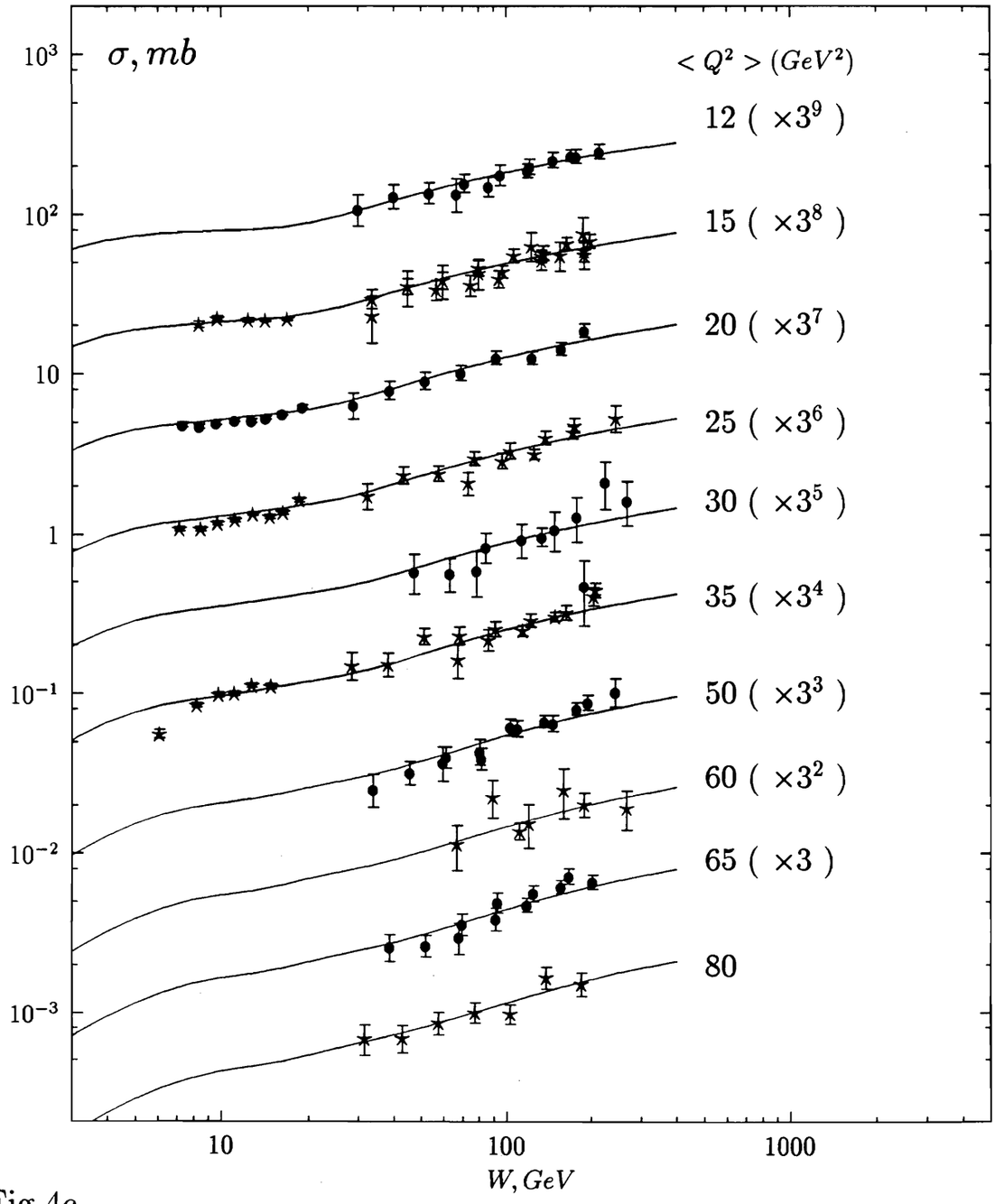
σ, mb
$< Q^2 > (GeV^2)$
12 ($\times 3^9$)
15 ($\times 3^8$)
20 ($\times 3^7$)
25 ($\times 3^6$)
30 ($\times 3^5$)
35 ($\times 3^4$)
50 ($\times 3^3$)
60 ($\times 3^2$)
65 ($\times 3$)
80
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10
100
1000
W, GeV

Fig.4c

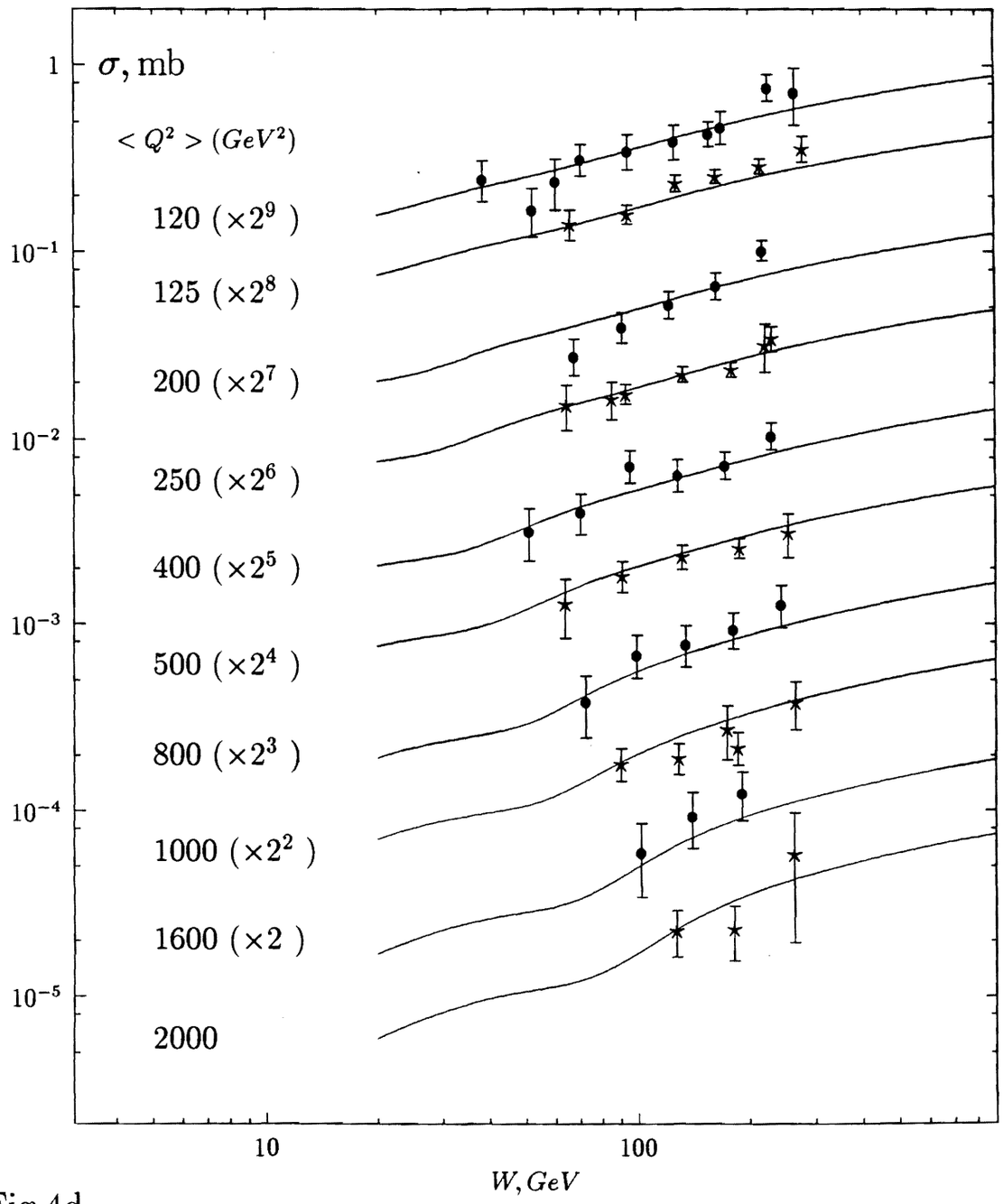
σ, mb
< Q² > (GeV²)
120 (×2⁹)
125 (×2⁸)
200 (×2⁷)
250 (×2⁶)
400 (×2⁵)
500 (×2⁴)
800 (×2³)
1000 (×2²)
1600 (×2)
2000
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10
100
W, GeV

Fig.4d