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Does F_2 need a hard pomeron?

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Abstract

We show that the latest HERA measurements of F_2 are compatible with the existence of a triple pole at $J = 1$. Such a structure also accounts for soft forward hadronic amplitudes, so that the introduction of a new singularity is not necessary to describe DIS data.

The latest data from HERA [1, 2, 3] have attained such a level of precision that they can constrain quite stringently the possible singularity structures in the complex J plane which control the s dependence of soft hadronic amplitudes at $t = 0$ and the x dependence of F_2. Traditionally, it has been assumed that soft hadronic amplitudes would be constrained by their analytic properties, *i.e.* by Regge theory, whereas DIS would be the domain where perturbative QCD could be tested, with an overlap at only extremely small x. However, it has recently been realised [4, 5] that there is no reason to limit the application of Regge theory to such a domain. Indeed, hadronic scattering amplitudes are the continuation of t-channel scattering amplitudes, and the simple structures predicted by Regge theory become valid once the cosine of the t-channel scattering angle, $\cos\theta_t$, becomes sufficiently large. One can in fact quantify this in the hadron-hadron case, as the forward scattering amplitudes (measured through ρ and σ_{tot}) are well fitted for $\sqrt{s} > 10$ GeV. This corresponds, in the pp and $\overline{p}p$ cases, to a value of

$$\cos\theta_t = \frac{s}{2m_p^2} \geq 57. \quad (1)$$

In the $\gamma^* p$ case, the total cross section,

$$\sigma_{\gamma^* p} = \frac{4\pi^2\alpha_{elm}}{Q^2} F_2(x, Q^2), \quad (2)$$

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should be described by the same singularities for the same region of $\cos\theta_t = \nu/(m_p\sqrt{Q^2}) = \sqrt{Q^2}/(2m_p x)$. Hence one would expect to observe the same singularities in F_2 and in total hadronic cross sections for values

$$x \leq \frac{\sqrt{Q^2}}{100 m_p}. \tag{3}$$

This is a rather large interval where there is considerable overlap with standard perturbative QCD evolution, hence one would hope for the two descriptions to become compatible (but we are not yet at a stage to show this result). Whether it makes sense to extend Regge fits to larger x [6, 7] or to smaller s [7] remains debatable.

The problem in implementing such a program is that, although the same singularities have to be present, their residues are not known, and must be Q^2-dependent. It is known however that the Q^2 dependence must enter only in the residues, *i.e.* the ν dependence should not change with Q^2. As the effective ν dependence does seem to vary as Q^2 increases at HERA, this can only be obtained by combining several singularities, and writing

$$F_2(\frac{Q^2}{2\nu}, Q^2) = \sum_i g_i(Q^2) f_i(\nu) \tag{4}$$

with the f_i resulting from the singularities observed in fits to total cross sections [8]. The fact that the residues depend on Q^2 means that some singularities may remain hidden in soft scattering amplitudes, and manifest themselves only at high Q^2. However, as the values of Q^2 observed now at HERA span the whole range from 0.045 to 30000 GeV^2, it seems unlikely that such singularities would switch off totally in total cross sections[3].

The first model proposing such a global fit is due to Donnachie and Landshoff [4] and is based on their previous model [10] based on a simple-pole singularity, which accounts very successfully not only for hadronic total cross sections, but also for elastic and diffractive scattering [10]. The problem is that, at small x, this model predicts a single singularity in (4), and hence the effective power of x cannot change with Q^2. This lead Donnachie and Landshoff to postulate the existence of a hidden singularity, called the hard pomeron, which is needed to reproduce the rise of F_2 at small x, but which is totally absent from total hadronic cross sections, with residues at least 10^6 times smaller than those of the soft pomeron [8]. It is rather hard to imagine how such a fierce singularity can totally turn off in hadron-hadron scattering, as the hadrons will sometimes fluctuate into small systems of quarks, comparable to those produced by the off-shell photons. Furthermore, the model seems to require the soft pomeron to turn off in F_2^c, whereas it is needed in J/ψ production. Although one cannot prove that these features are excluded, they seem rather unnatural. Nevertheless, the model reproduces quite well the new data from HERA, and can even be extended outside the area of applicability of Regge theory [6].

[3]It is however also possible to argue that the photon is special, and that t-channel unitarity relations, from which the universality of residues is derived [9], do not form a closed system for photons, hence they could have exceptional singularities.

There are other alternative fits to total cross sections [7, 12] (for a review see [8, 11]) which work equally well, or better, than simple poles. In such models, the rise of total cross sections is assumed to come from a double pole, or a triple pole, at $J = 1$.

In the first case [7], the fit to soft amplitudes forces one to assume a large splitting of the intercepts of leading meson trajectories, which means that such trajectories must be non linear. Furthermore, the leading $C = +1$ contribution becomes negative at sufficiently small s, of the order of 10 GeV, and factorisation would naively lead to negative total cross sections for processes which couple only to the leading trajectories. Although once again these points cannot be used to rule the model out (as neither factorisation of double poles nor the linearity of meson trajectories can be proven), they make it seem unnatural.

The second candidate [12] does not have these drawbacks, and the description of total cross sections that it provides can even be extended down to $\sqrt{s} = 5$ GeV [11]. Not only does it fit well both total cross sections, and values of the ρ parameter for forward hadronic amplitudes, but the outcome of such a fit seems the most natural: unitarity is preserved, the various $C = +1$ terms of the cross section remain positive, and the meson trajectories are compatible with exchange degeneracy. We shall show here that this fit extends naturally to reproduce DIS data, at least in the Regge region (3).

We shall adopt here the natural Regge variable 2ν instead of W [7], as this makes a sizable difference in the large-x region, and we shall assume that F_2 can be fitted by

$$F_2(\frac{Q^2}{2\nu}, Q^2) = a(Q^2) \log^2 \left(\frac{2\nu}{2\nu_0(Q^2)} \right) + c(Q^2) + d(Q^2)(2\nu)^{-0.47} \tag{5}$$

in the region (3). The first two terms represent pomeron exchange, and the third a/f exchange. We have fixed the intercept of the latter from fits to hadronic amplitudes [8, 11].

The first test to check whether such a simple form has a chance to reproduce the data is to follow [4] and extract the residues $a(Q^2)$, $c(Q^2)$, $d(Q^2)$ and the scale $b(Q^2) \equiv \log(2\nu_0(Q^2))$ by fitting the ν dependence for each value of Q^2.

As explained above, we limit ourselves to a consideration of the data in the region (3), and to Q^2 bins where there are at least 10 data points. We show in Fig. 1 the result of such a fit (to a total of 875 points), which corresponds to having one parameter for each residue and for each value of Q^2. This fit has a χ^2 per data point of 0.674, compared with 1.00 for the hard pomeron model of [4] refitted to those data. Hence it seems that *a priori* the data are as compatible with (5) as with the fits of [4, 6]. The graphs represent the coefficients respectively of the $\log^2(2\nu)$, $\log(2\nu)$ and constant terms. We see that the data do exhibit a suppression at small Q^2, and there is a strong correlation between the three terms, which all seem to have a similar behaviour with Q^2.

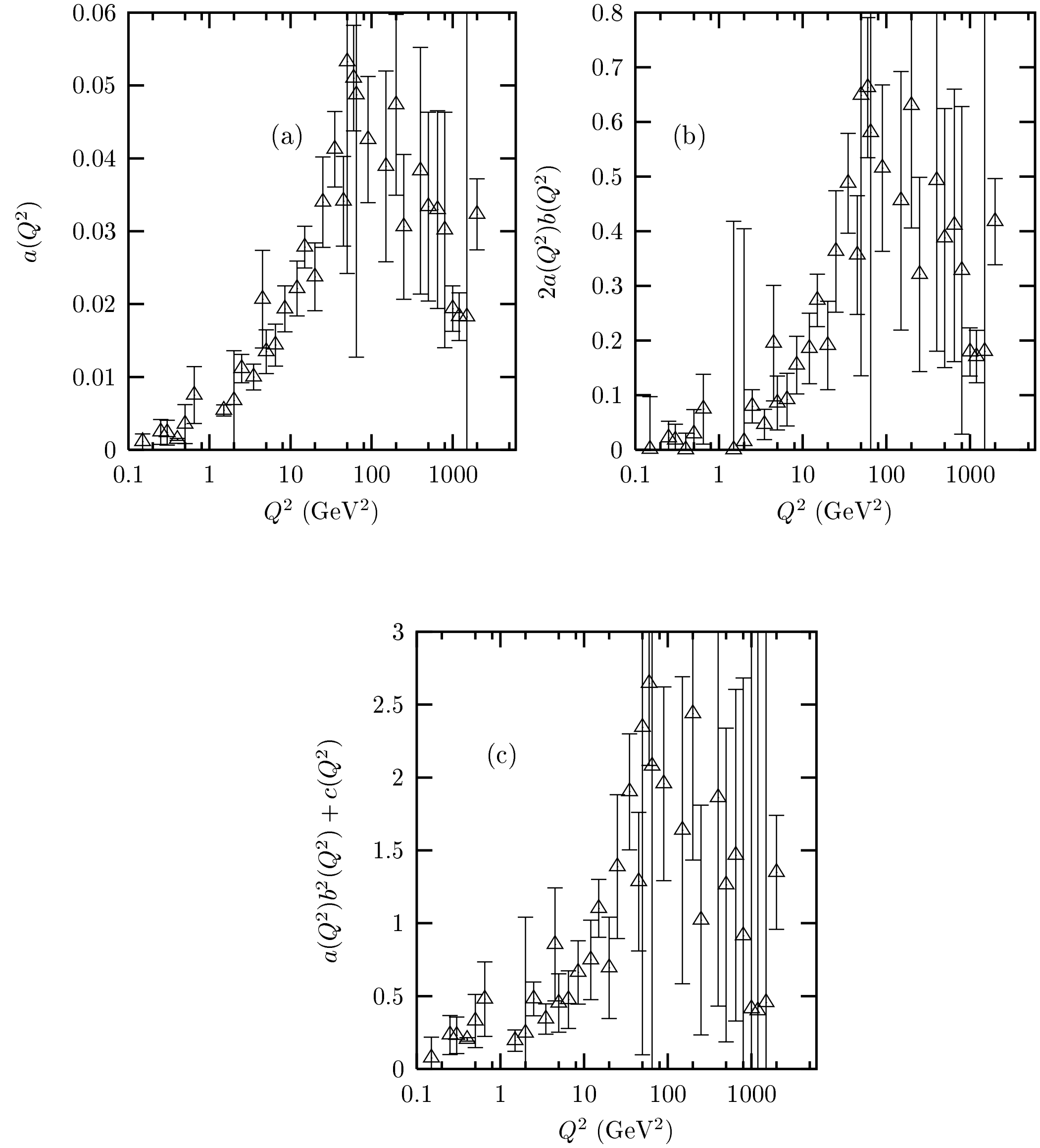

Figure 1: the coefficients (a) of $\log^2(2v)$, (b) of $\log(2\nu)$ and (c) of the constant term, extracted from the latest HERA data.

We can now proceed to a parametrisation of the residues. We first consider the data of refs. [1, 2], which extend to $Q^2 = 135$ GeV^2, as they are almost entirely in region (3), together with data for the total γp cross section [13] at $\sqrt{s} >5$ GeV[4]. Apart from the fact that gauge invariance imposes that the form factors vanish linearly at $Q^2 \to 0$ for fixed ν, their form is undetermined. We find that a good fit is obtained by the following forms:

$$g(Q^2) = A_g Q^2 \left(\frac{1}{1+Q^2/Q_g^2}\right)^{\epsilon_g}, \; g = a,\, c,\, d \tag{6}$$

[4]As the data from 5 to 10 GeV have big error bars, it makes little difference whether we include them or not.

$$b(Q^2) = \log\left[2\nu_0(Q^2)\right] = b_0 + b_1\left(\frac{Q^2}{Q^2+Q_b^2}\right)^{\epsilon_b} \tag{7}$$

$Q^2 \leq 135$ GeV^2			$Q^2 \leq 30000$ GeV^2		
parameter	value	error	parameter	value	error
A_a	0.00981	0.0031	A_a	.99383E-02	.17197E-03
Q_a	0.992	0.125	Q_a	1.8850	.74726E-01
ϵ_a	0.721	0.026	ϵ_a	.89988	.10849E-01
A_c	0.945	0.008	A_c	.95727	.38888E-02
Q_c	0.696	0.035	Q_c	.62391	.16433E-01
ϵ_c	1.34	0.04	ϵ_c	1.3903	.23285E-01
A_d	0.430	0.066	A_d	.27401	.27215E-01
Q_d	0.260	0.367	Q_d	31.987	5.5734
ϵ_d	0.451	0.104	ϵ_d	1.6884	.15020
b_0	3.00	0.641	b_0'	3.00	.91789E-02
b_1	3.31	0.27	b_1'	.13797	.54106E-01
Q_b	18.2	8.92	Q_b'	4.6269	1.6797
ϵ_b	3.16	1.26	ϵ_b'	1.8551	.15402

Table 1: the values of the parameters corresponding to Eqs. (6, 7) for the low-to-intermediate Q^2 fit, and those of the global fit to region (3), corresponding to Eqs. (6,8).

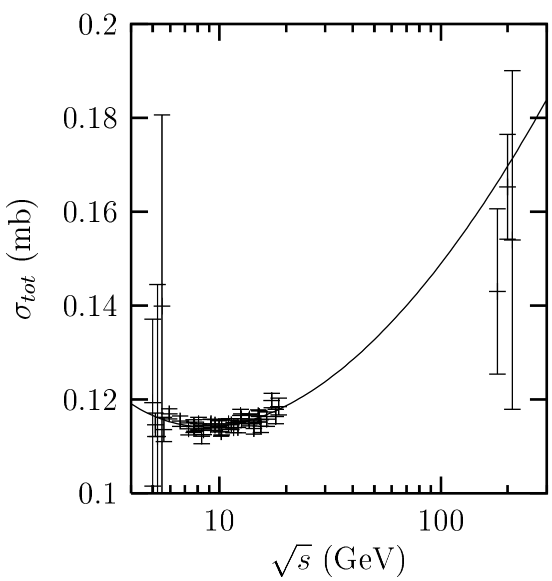

Figure 2: fit to the total cross section data for $\sqrt{s} \geq 5$ GeV.

The resulting values of the parameters are given in Table 1. We imposed that the fit smoothly reproduces the value of $\nu_0(0)$ which results from a global fit to all hadronic cross sections [8]. The fit gives a χ^2 of 185.2 for 241 points (including 38 points for the total cross section), which is somewhat better than those of [6, 7]. We show in Figs. 2 and 3 the curves corresponding to these results.

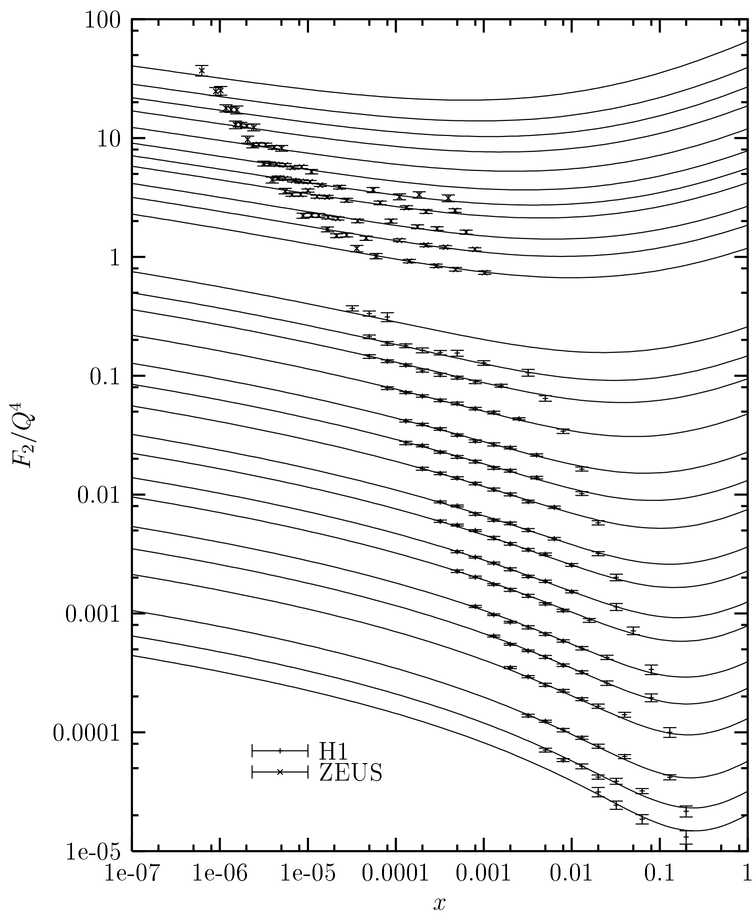

Figure 3: fit to the new HERA data [1, 2] for $Q^2 \leq 135$ GeV^2.

It is interesting to note that such simple forms for the residues, which achieve a remarkably low χ^2 up to 135 GeV^2, do not extend well beyond 500 GeV^2. Whether one wants to go beyond this result is really a matter of taste. As we have explained, it is possible to have "hidden" singularities, which would manifest themselves only as Q^2 becomes large enough. From a perturbative QCD point of view, the present fit can be seen as a starting point for $F_2(x, Q^2)$, consisting of constants, $\log x$ and $\log^2 x$ terms.[5] Perturbative evolution will then

[5]One must note however that we have not tried to go beyond the Regge region, and hence the limit $x \to 1$ is not correct, as F_2 should go to 0 there.

produce further $\log x$ terms, which would be hidden below the starting evolution scale. As singularities of hadronic amplitudes cannot occur at arbitrary places, the latter would have to be a physical parameter, and the present fit shows that it should be of order $Q_0 = 10$ GeV [14].

It may be a worthwhile exercise however to check whether this singularity structure can be extended to the full Regge region, and to consider a fit to the full dataset of DIS [15]. The reason is that in this case there is considerable overlap between the DGLAP region (Q^2 large, $\log Q^2 \gg -\log x$) and the Regge region (3), and hence one should be able to understand some features of the pomeron through perturbative means. In this region, to achieve values of χ^2 comparable to those of [6, 7], we need in fact to modify the form used for the scale $\nu_0(Q^2)$, and introduce a logarithm in its expression:

$$b(Q^2) = b_0 + b_1' \left[\log\left(1 + \frac{Q^2}{Q_b'^2}\right)\right]^{\epsilon_b'}. \tag{8}$$

Such a form allows us to extend the fit to the full Regge region (3), and produces a reasonable χ^2/dof: we obtain 1411 for 1166 points (including 21 points for the total cross section above $\sqrt{s} = 10$ GeV)[6], but the χ^2 for the new HERA points [1, 2] gets degraded to 311. This is largely due to the tiny size of the errors on the new data, and to some inconsistencies in the full dataset. A fine-tuning of the form factors [7] could presumably lead to a better χ^2, but what we would learn from such an exercise is unclear. We show in Fig. 4 the results of this global fit, and, as we can see, the full Regge region (3) is well accounted for. Note that although all the data are fitted to, we show only the data from HERA, as the number of values of Q^2 would otherwise be too large to represent in this manner.

In conclusion, we see that several scenarios compatible with Regge theory are possible to describe structure functions. All of them share the characteristic that one needs several component to describe DIS and soft scattering at the same time. We believe that the present parametrisation shows that no unexpected behaviour is needed to reproduce DIS, and that the pomeron may well be a single object, connecting all regions of Q^2 smoothly, and exhibiting the same singularities in DIS and in soft scattering. How to obtain such a simple form in the region of overlap between perturbative QCD and Regge theory remains an open question.

Acknowledgements

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[6]Note that the fit of [6] give a χ^2 of 3941 on those points.

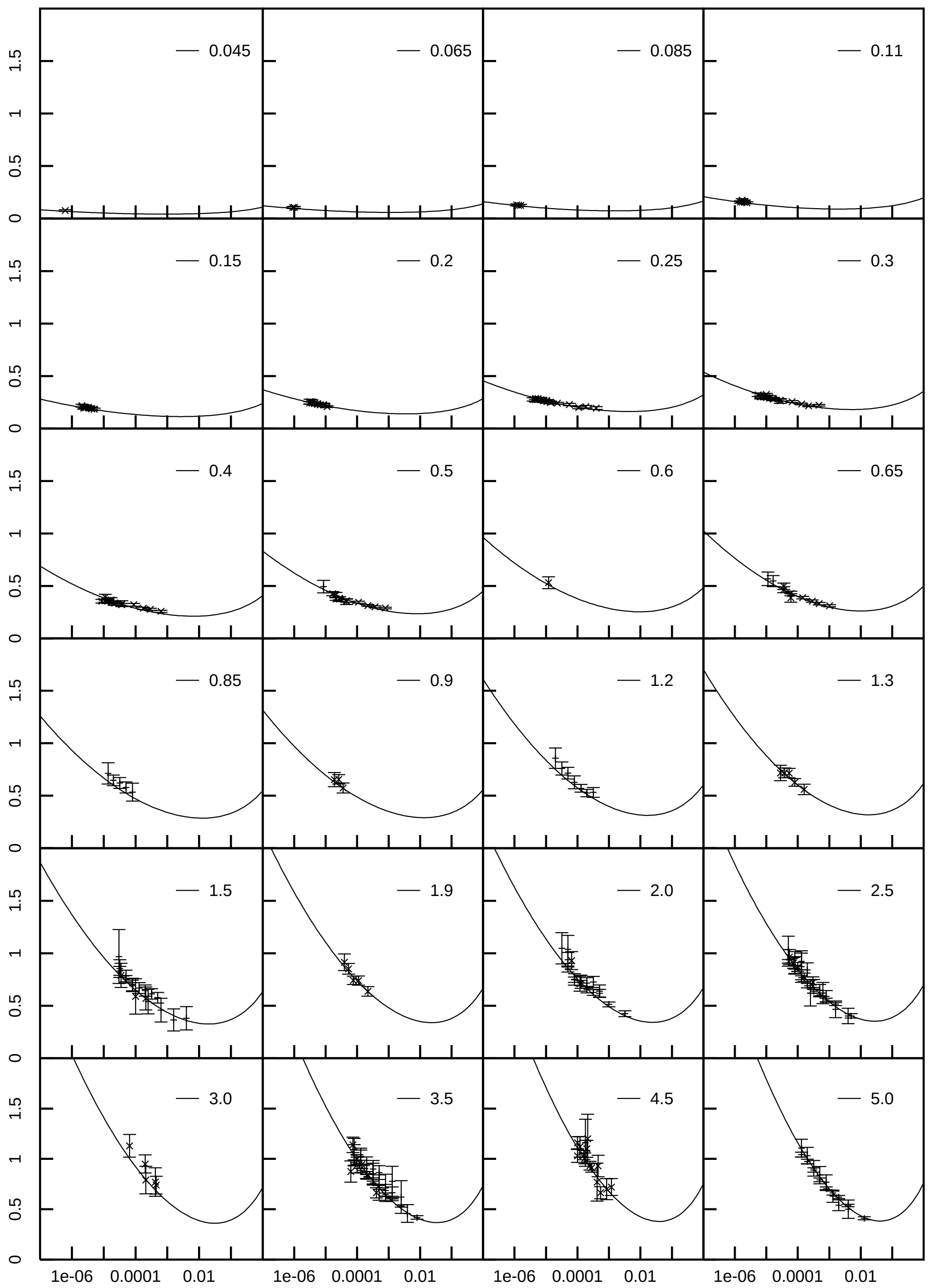

Figure 4 (a): Result of a global fit to all the data in the Regge region, for $0.045 \leq Q^2 \leq 5.0$ GeV^2. $F_2(x, Q^2)$ is shown as a function of x, for each Q^2 value indicated (in GeV^2). Only data from HERA are shown.

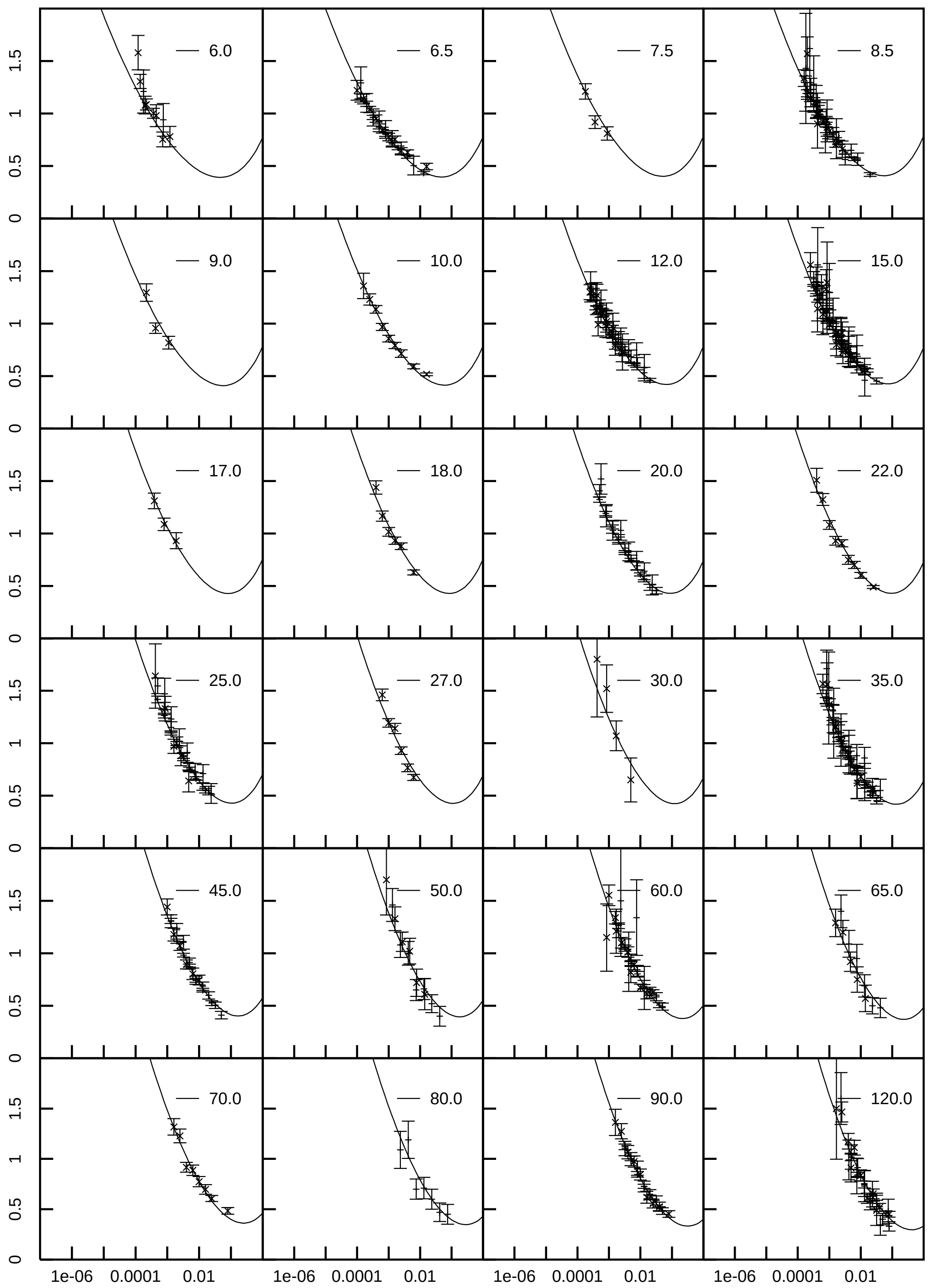

Figure 4 (b): Result of a global fit to all the data in the Regge region, for $6.0 \leq Q^2 \leq 120.0$ GeV^2. $F_2(x, Q^2)$ is shown as a function of x, for each Q^2 value indicated (in GeV^2). Only data from HERA are shown.

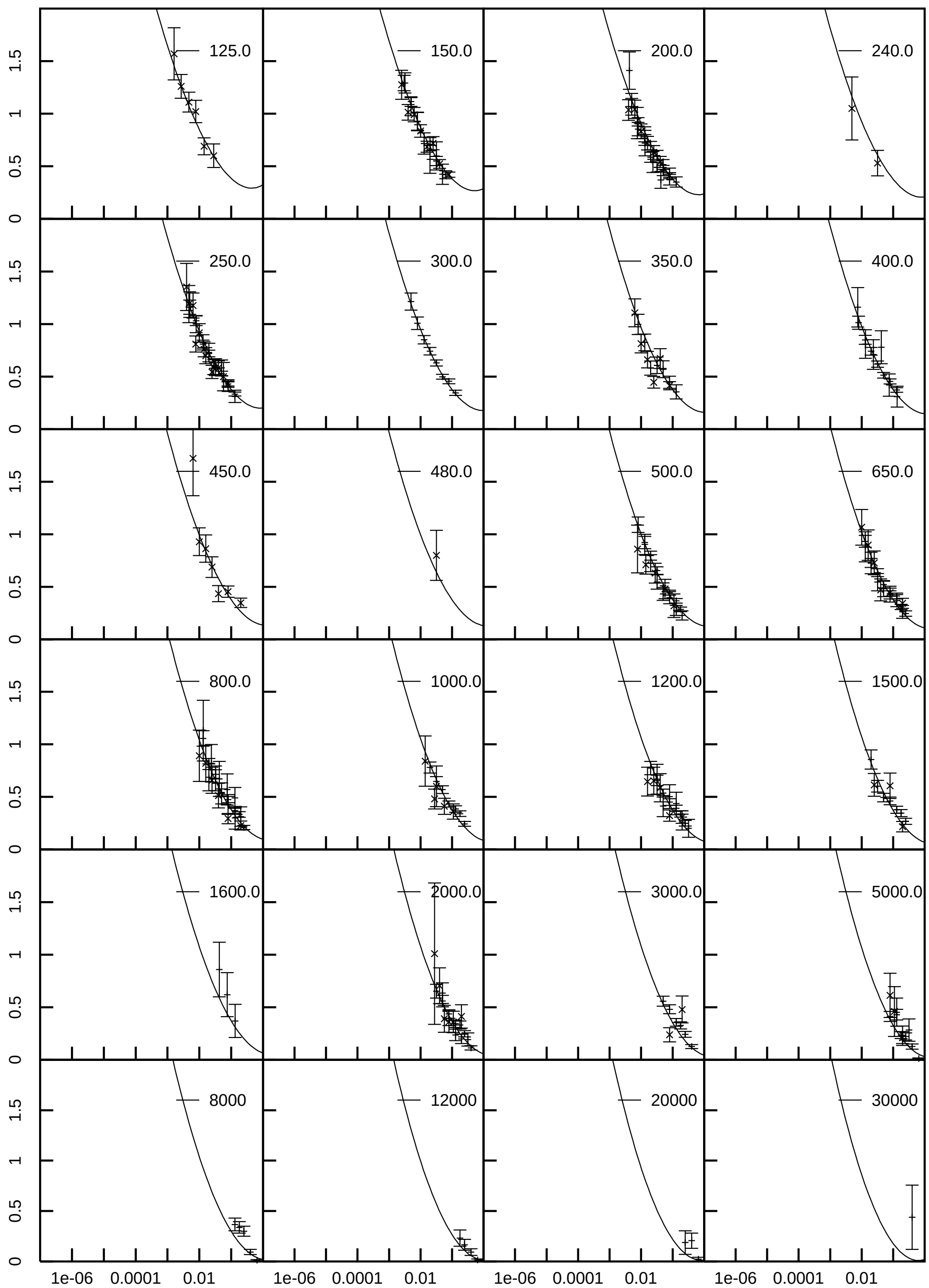

Figure 4 (c): Result of a global fit to all the data in the Regge region, for $125.0 \leq Q^2 \leq 30000.0$ GeV^2. $F_2(x, Q^2)$ is shown as a function of x, for each Q^2 value indicated (in GeV^2). Only data from HERA are shown.

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[15] available at the URL http://www-spires.dur.ac.uk/HEPDATA/online/f2/structindex.html, and to which we added the latest HERA data [1, 2, 3].