

# SMALL $x$ : TWO POMERONS!

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## Abstract

Regge theory provides a very simple and economical description of data for (i) the proton structure function with  $x < 0.07$  and all available  $Q^2$  values, (ii) the charm structure function, and (iii)  $\gamma p \rightarrow J/\psi p$ . The data are all in agreement with the assumption that there is a second pomeron, with intercept about 1.4. They suggest also that the contribution from the soft pomeron is higher twist.

This means that there is an urgent need to make perturbative evolution compatible with Regge theory at small and not-so-small  $x$ , and to reassess the magnitude of higher-twist contributions at quite small  $x$ .

Regge theory is one of the great truths of particle physics<sup>[1]</sup>. It is supposed to be applicable if  $W^2$  is much greater than all the other variables. Thus, we expect it to be valid when  $x$  is small enough, even for large values of  $Q^2$ . Fits to large- $Q^2$  data have traditionally concentrated on perturbative evolution; in this paper we report fits that rather emphasise the Regge behaviour. Regge behaviour is not a substitute for perturbative evolution, but a constraint on it, and an important task will be to understand better how the two coexist. Somewhat surprisingly, we find that Regge behaviour is compatible with the data even for values of  $x$  up to 0.07 or higher.

Regge theory involves pomerons. Until HERA measurements of the proton structure function<sup>[2]</sup> at very small- $x$ , and of  $J/\psi$  photoproduction<sup>[3]</sup>, it seemed consistent to suppose<sup>[4]</sup> that a single nonperturbative pomeron with intercept close to 1.08 describes the whole of diffractive physics, including<sup>[5]</sup> the NMC and E665 structure function data at fairly small  $x$ . The more violent behaviour observed at HERA calls rather for an intercept closer to 1.5 than 1.0, and there has been much discussion of what is responsible for this.

One view<sup>[6]</sup> is that the pomeron intercept varies with  $Q^2$ , but we find this difficult to believe. Regge theory relates<sup>[1]</sup> the  $W$ -dependence of a process to the positions of singularities in the complex angular momentum plane, and it does not naturally accommodate the notion that these positions vary with  $Q^2$ . The relative weights of the contributions from these singularities can, however, vary with  $Q^2$ ,

and so the effective power resulting from combining them can be  $Q^2$ -dependent. We find less than persuasive the hypothesis<sup>[7]</sup> that in soft processes there is a significant amount of shadowing, so that the observed effective intercept of 1.08 actually is the result of the pomeron having a significantly larger intercept, and that the rapid rises observed at HERA are merely the result of the disappearance of the shadowing. If there is a significant amount of shadowing, the apparent intercept should be process-dependent, but all soft processes are found<sup>[8]</sup>, to a remarkable accuracy, to have the same value.

In this paper, therefore, we explore the notion that there are two pomerons. It is a good working principle always first to try the simplest assumptions, so we assume that each is a simple pole in the complex angular momentum plane, making the contribution from each a simple power of  $W$ , multiplied by an unknown function of  $Q^2$ . Thus

$$F_2(x, Q^2) = \sum_i f_i(Q^2) x^{-\epsilon_i} \quad (1)$$

Bearing in mind that the cross section for the absorption of real photons is

$$\sigma^{\gamma p} = \frac{4\pi^2 \alpha_{EM}}{Q^2} F_2 \Big|_{Q^2=0} \quad (2)$$

we require each  $F_2(x, Q^2)$  to vanish linearly with  $Q^2$  at fixed  $W$ , so that presumably  $f_i(Q^2)$  vanishes like  $(Q^2)^{1+\epsilon_i}$ . Beyond the fact that, presumably, they are smooth functions of  $Q^2$ , this is the only information that we have about the form of the  $f_i(Q^2)$ . In the past<sup>[9][5]</sup>, we used the simplest possible forms:

$$f_i(Q^2) = A_i \left( \frac{Q^2}{Q^2 + a_i} \right)^{1+\epsilon_i} \quad (3)$$

and just two terms, with powers

$$\begin{aligned} \epsilon_1 &= 0.0808 && \text{(soft pomeron exchange)} \\ \epsilon_2 &= -0.4525 && \text{( $f, a$  exchange)} \end{aligned} \quad (4)$$

Now, we retain the same two powers  $\epsilon_1$  and  $\epsilon_2$ , and we add a third term ( $i = 0$ ), which we call hard-pomeron exchange.

As we have said, Regge theory is supposed to be applicable if  $W^2$  is much greater than all the other variables. Thus, we expect it to be valid when  $x$  is small enough, whatever the value of  $Q^2$ . Just what is meant by small enough is open to debate: we shall assume, as we have before<sup>[5]</sup>, that it means

$$x < 0.07$$

and, in the case of the real-photon data,  $\sqrt{s} > 6$  GeV, though it is worth remembering that these choices are somewhat arbitrary.

Because Regge theory gives us no information about the  $Q^2$  dependence of the various contributions, we should not expect our simple guess (3) for the coefficient functions  $f_i(Q^2)$  to work for arbitrarily large  $Q^2$ . So initially, again as before<sup>[5]</sup>, we used it to extract a preliminary value for the power  $\epsilon_0$  by applying it to all data for which

$$Q^2 < 10 \text{ GeV}^2$$

including  $Q^2 = 0$ . We then abandoned the simple form (3), and used this preliminary value for  $\epsilon_0$  to fit at each value of  $Q^2$ , and so found how the data require the coefficient functions  $f_i(Q^2)$  to behave at all available values of  $Q^2$ . This suggested how we should parametrise the functions  $f_i(Q^2)$ , and with these parametrisations we then began the fitting exercise afresh.

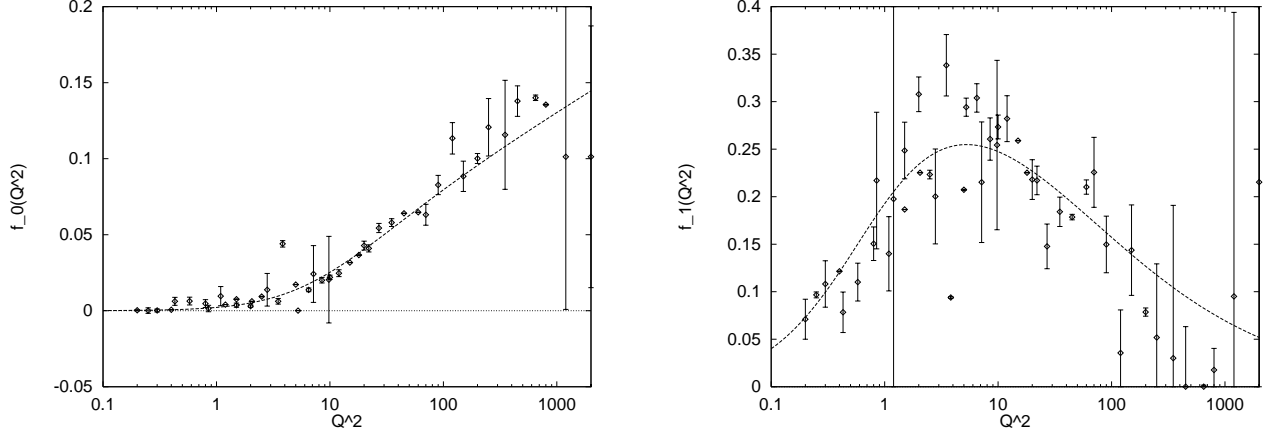


Figure 1: Best fits to the coefficient functions  $f_0(Q^2)$  and  $f_1(Q^2)$ , at each  $Q^2$  for which there are data with  $x < 0.07$ , together with curves corresponding to the fit (6) and (7).

The simple form (3) gave  $\chi^2 = 1.075$  per data point\*, for the 280 data points with  $Q^2 < 10$ , with parameter values

$$\begin{aligned}
 \epsilon_0 &= 0.435 \\
 A_0 &= 0.0358 & a_0 &= 5.41 \\
 A_1 &= 0.274 & a_1 &= 0.504 \\
 A_2 &= 0.149 & a_2 &= 0.0196
 \end{aligned} \tag{5}$$

We have given each parameter to high accuracy because a small change in any one parameter has a significant effect on the  $\chi^2$  of the fit. This does not mean that the parameters are determined to that accuracy, because the  $\chi^2$  minimum is not very sharp and a change in any one parameter can be compensated by changes in all the others in such a way as not to have much effect on the  $\chi^2$ .

For larger  $Q^2$ , we find that the simple  $Q^2$  dependences make the coefficient function of the  $x^{-\epsilon_0}$  term too small, and that of  $x^{-\epsilon_1}$  too large. For each value of  $Q^2$  for which we have data with  $x < 0.07$ , we made a best fit using the form (1) keeping the same simple shape (3) for the  $f, a$  contribution and with the values of all the quantities except  $f_0(Q^2)$  and  $f_1(Q^2)$  taken over from the fit to the  $Q^2 < 10$  data. The resulting values for  $f_0(Q^2)$  and  $f_1(Q^2)$  are shown in figure 1, where the error bars are produced from MINUIT. Obviously one can fit these with a variety of functions. We have tried several. Our lowest overall  $\chi^2$  corresponds to the choices

$$\begin{aligned}
 f_0(Q^2) &= A_0 \left( \frac{Q^2}{Q^2 + a_0} \right)^{1+\epsilon_0} \left( 1 + X \log \left( 1 + \frac{Q^2}{Q_0^2} \right) \right) \\
 f_1(Q^2) &= A_1 \left( \frac{Q^2}{Q^2 + a_1} \right)^{1+\epsilon_1} \frac{1}{1 + \sqrt{Q^2/Q_1^2}} \\
 f_2(Q^2) &= A_2 \left( \frac{Q^2}{Q^2 + a_2} \right)^{1+\epsilon_2}
 \end{aligned} \tag{6}$$

We vary all the parameters except  $\epsilon_1$  and  $\epsilon_2$ . This 10-parameter fit gave a minimum  $\chi^2 = 1.016$  per data point for 539 data points with the parameter values

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\* In our calculations of  $\chi^2$  we have folded the systematic and statistical errors in quadrature.

$$\begin{aligned}
& \epsilon_0 = 0.418 \\
A_0 = 0.0410 & \qquad \qquad \qquad a_0 = 7.13 \\
& \qquad \qquad \qquad X = 0.485 \qquad \qquad Q_0^2 = 10.6 \\
A_1 = 0.387 & \qquad \qquad \qquad a_1 = 0.684 \qquad \qquad Q_1^2 = 48.0 \\
A_2 = 0.0504 & \qquad \qquad \qquad a_2 = 0.00291 \qquad \qquad \qquad (7)
\end{aligned}$$

The same comments as before must be made about the accuracies of these parameters. Figures 2, 3 and 4 show the fits they give to the data.

We have a number of comments to make:

1. Our fits show that, at small enough  $x$ , the data may be fitted by a combination of three fixed powers of  $x$ . This is in accord with the Regge-theory expectation if, at least to a good approximation, the singularities in the complex angular momentum plane are simple poles. We have used as input the same powers,  $\epsilon_1 = 0.0808$  and  $\epsilon_2 = -0.4525$ , for soft pomeron and  $f, a$  exchange as in our previous fits<sup>[4]</sup>, though these values have recently been questioned by Cudell et al<sup>[10]</sup>. Instead of (4), they advocate  $\epsilon_1 = 0.094$  and  $\epsilon_2 = -0.33$ . With these values, and the form (6) for the coefficient functions  $f_i(Q^2)$ , our  $\chi^2$  per data point would reduce to 0.98, with  $\epsilon_0 = 0.410$ , though whether this reduction is significant is doubtful, since our  $\chi^2$  is already so close to 1.

2. There may be a significant error on our output hard-pomeron power  $\epsilon_0 = 0.418$ , perhaps  $\pm 0.05$ . For example, if one were to decide that the value  $a_2 = (53.9 \text{ MeV})^2$  in (7) is too small to be physically reasonable, then increasing it to the square of the pion mass increases the  $\chi^2$  per data point to 1.032, and so still gives a good fit, but it reduces  $\epsilon_0$  to 0.388. Alternatively, if we prefer to have the coefficient function  $f_1(Q^2)$  for the soft pomeron go to zero at large  $Q^2$  like  $1/Q^2$  instead of  $1/Q$ , so that we replace  $\sqrt{Q^2/Q_1^2}$  in (6) with  $Q^2/Q_1^2$ , the  $\chi^2$  per data point becomes 1.018 with  $\epsilon_0 = 0.462$ .

3. This makes it clear that the exact forms we have used for the  $Q^2$  dependences of the three contributions should not be taken too seriously: Regge theory has nothing to say about them and we have chosen the simplest forms that work. Nevertheless, we can be reasonably confident that, as is seen in figure 1, the soft-pomeron term has a coefficient that rises to a maximum somewhere between  $Q^2 = 5$  and 10, and it is very likely that it goes to zero at high  $Q^2$ . The hard and soft pomeron contributions to  $F_2$  are shown in figure 5 at two values of  $Q^2$ ; they move in opposite directions as  $Q^2$  increases, so that while the soft pomeron is important at  $Q^2 = 5$  it becomes less so at higher  $Q^2$ . The conclusion that the soft pomeron is higher twist is one that we did not expect and implies that all fits based on conventional evolution that have been made so far need to be reassessed. It is reminiscent of a suggestion of McDermott and Forshaw<sup>[11]</sup>, who indeed have a next-to-leading contribution that goes to zero as  $1/Q$  at high  $Q^2$ . Their leading term rises like  $Q$  at high  $Q^2$ ; the data are not inconsistent with this: we find it gives a  $\chi^2$  per data point of 1.072, with  $\epsilon_0 = 0.385$ . But our logarithmic form, which presumably corresponds more to DGLAP evolution, gives a better fit – though we emphasise that Regge theory requires that the perturbative evolution should be applied in such a way that, at small  $x$ , it does not cause the power  $\epsilon_0$  to change with  $Q^2$ .

4. We have said that our choice  $x < 0.07$  for the range of  $x$  in which we fit the data is arbitrary. Indeed, one might be surprised that the Regge region extends to such a large value of  $x$ . If we use instead only data for which  $x < 0.01$ , with the functional forms (6) for the coefficient functions  $f_i(Q^2)$  and the parameter values (7), the  $\chi^2$  improves from 1.016 per data point to 0.95 (with 357 data points).

5. There will be some who will object to fixed powers of  $x$  because of worries about unitarity. They will be wrong to do so, for several reasons. Firstly, we have shown that the fixed powers fit the data, and the data certainly respect whatever constraints unitarity may impose. Secondly, unitarity has

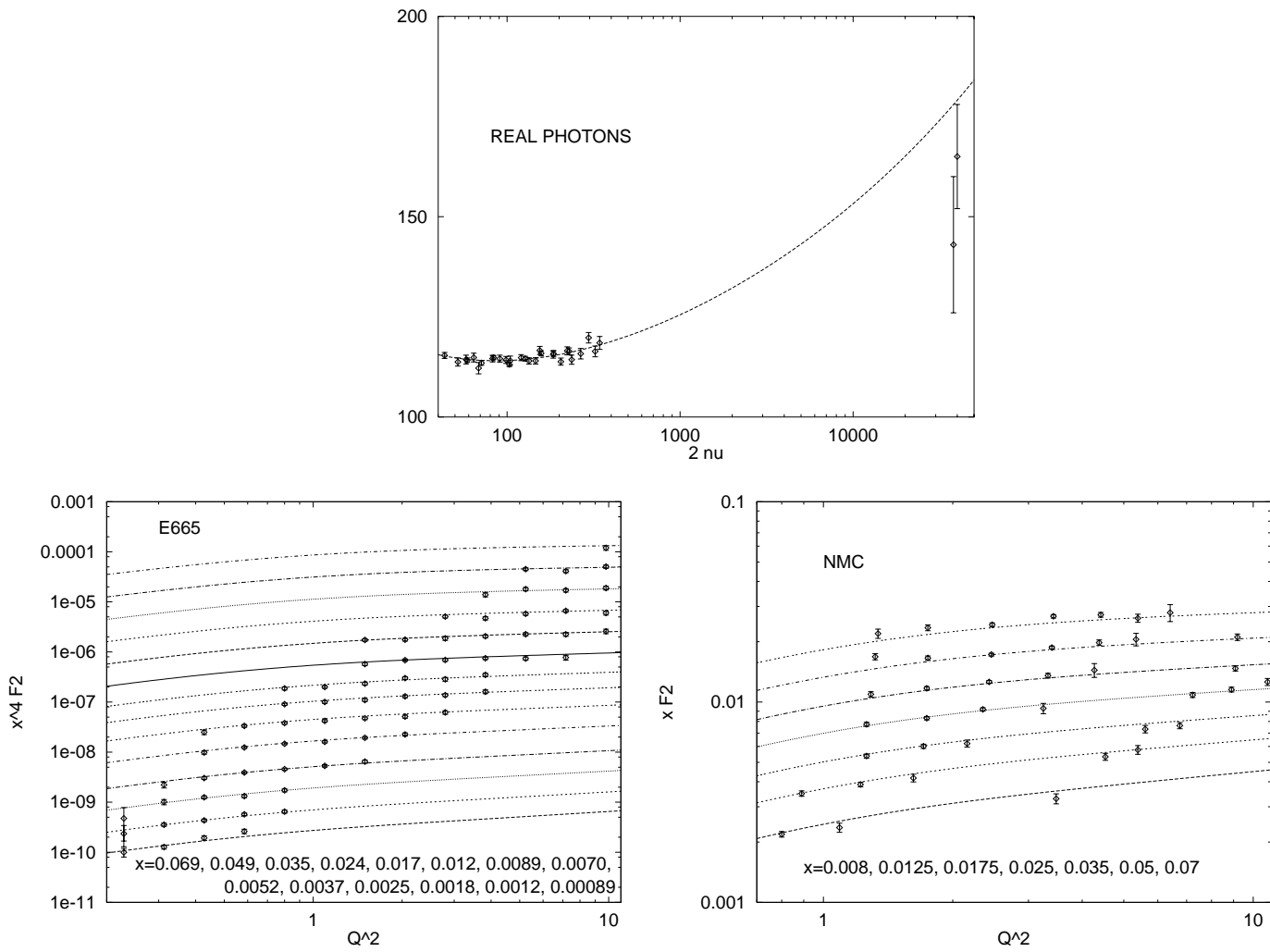


Figure 2: Fits to real-photon and small- $Q^2$  data. In the small- $Q^2$  plots the vertical axes are  $x^4 F_2$  and  $x F_2$ , so that the larger  $x$ -values are at the top.

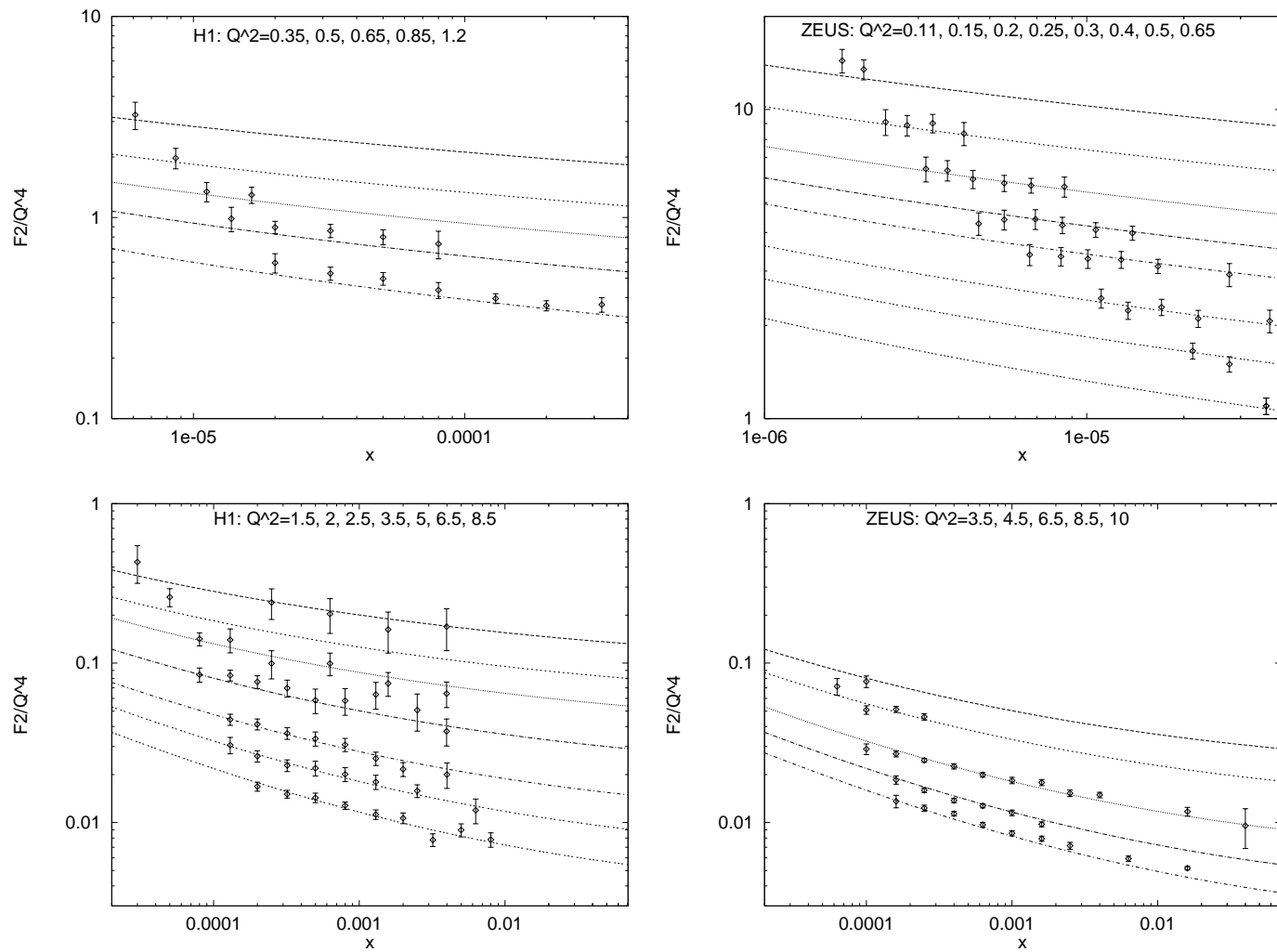


Figure 3: Fits to  $F_2$  data for  $Q^2$  between 0.11 and 10. The vertical scales are  $F_2/Q^4$ , so the smaller- $Q^2$  data are at the top

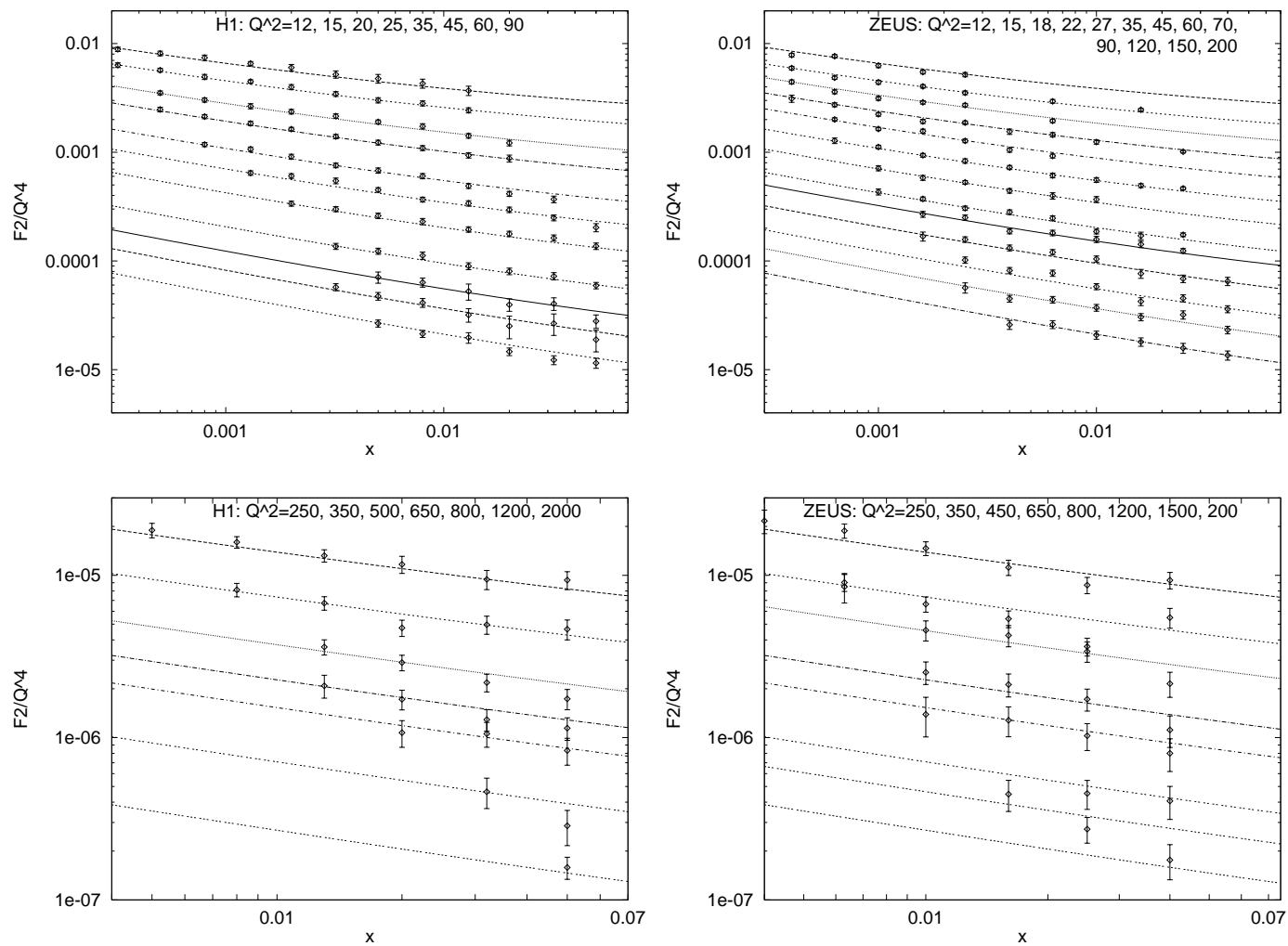


Figure 4: fits to large- $Q^2$  data. The vertical scales are  $F_2/Q^4$ , so the smaller  $Q^2$  values are at the top

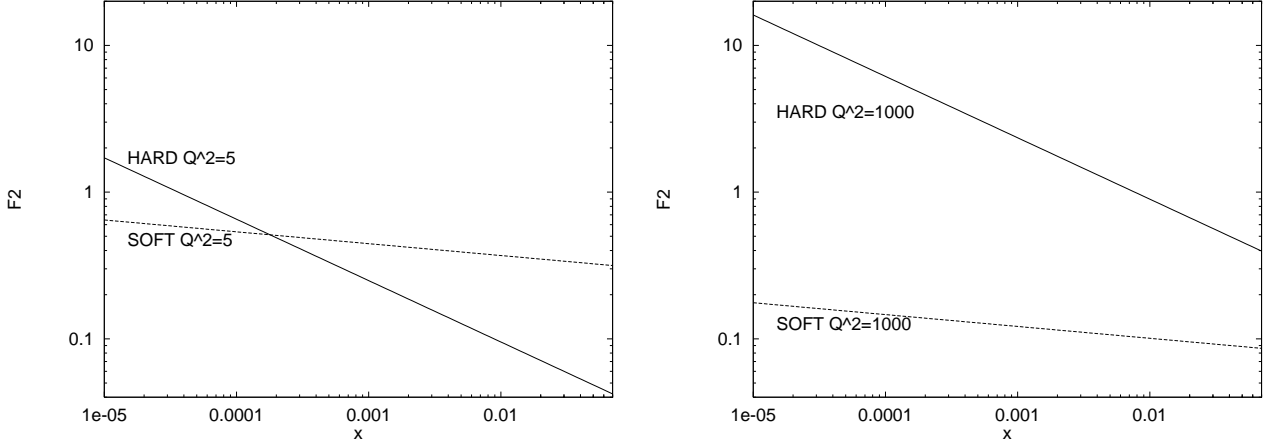


Figure 5: Relative magnitudes of hard and soft pomeron contributions at  $Q^2 = 5$  and 1000

nothing useful to say about structure functions anyway: the derivation of the unitarity constraints on a purely hadronic process such as  $pp$  scattering relies on the fact that a  $pp$  intermediate state appears in the unitarity equation; but  $\gamma^*p$  scattering is very different, because there is no  $\gamma^*p$  intermediate state. In any case, even in  $pp$  scattering, data at present energies are not seriously affected by unitarity constraints. The fact that a constant power fits the data well<sup>[4]</sup> indicates that, so far, shadowing corrections to the  $t = 0$  amplitude are small, though they will become more important at higher energies. Similarly, at extremely small  $x$  the fixed-power behaviour will be moderated by shadowing suppression, but there is no reason to believe that such small values have yet been achieved.

6. The accurate data for the low-energy real-photon cross-sections are an important constraint. If we make a best fit to the virtual-photon data alone, its extrapolation comes nowhere near the low-energy real-photon data. As can be seen in figure 2, our new fit extrapolates the small- $Q^2$  data to give a larger real-photon cross-section at HERA energies than in our old fits<sup>[4]</sup>. The ZEUS collaboration has reached a similar conclusion<sup>[12]</sup>, but it must be emphasised that it depends crucially on assuming a simple form for the  $Q^2$  dependence. There is no reason to rely on this, and by adopting more complicated extrapolations one can arrive at lower values<sup>[13]</sup>. We could even decouple the hard pomeron completely at  $Q^2 = 0$ . Nevertheless, it is interesting to note that preliminary results from a new ZEUS measurement of the real-photon total cross-section agree rather well with our curve<sup>[14]</sup>, which is

$$\begin{aligned} \sigma^{\gamma p} &= 4\pi^2\alpha_{\text{EM}} \sum_i A_i a_i^{-1-\epsilon_i} (2\nu)^{\epsilon_i} \\ &= 0.283 (2\nu)^{0.418} + 65.4 (2\nu)^{0.0808} + 138 (2\nu)^{-0.4525} \end{aligned} \quad (9)$$

with  $2\nu$  in  $\text{GeV}^2$  and the coefficients in  $\mu\text{b}$ , where  $2\nu = W^2 - m_p^2$ .

7. We have made the assumption that the  $Q^2$  dependences of the contributions to  $F_2$  from different flavours are the same, or at least that when the contributions are added together their sum has simple behaviour. This is not obviously true, and it is interesting to subject the recent accurate preliminary ZEUS data<sup>[12]</sup> for the charm content of  $F_2$  to our parametrisation. We find that they indicate that both the soft-pomeron and the  $f, a$  exchanges do not couple. The latter is readily understandable because of Zweig's rule, but the decoupling of the soft pomeron comes as something of a surprise. We impose

$$F_2^{c\bar{c}} = A_C \left( \frac{Q^2}{Q^2 + a_C} \right)^{1+\epsilon_0} (1 + X_C \log(Q^2/Q_C^2)) x^{-\epsilon_0} \quad (10)$$

with  $\epsilon_0 = 0.418$  as before. The data are not sufficient to determine the remaining four parameters well, so we choose to impose a constraint that the coupling of the hard pomeron is flavour-blind at large



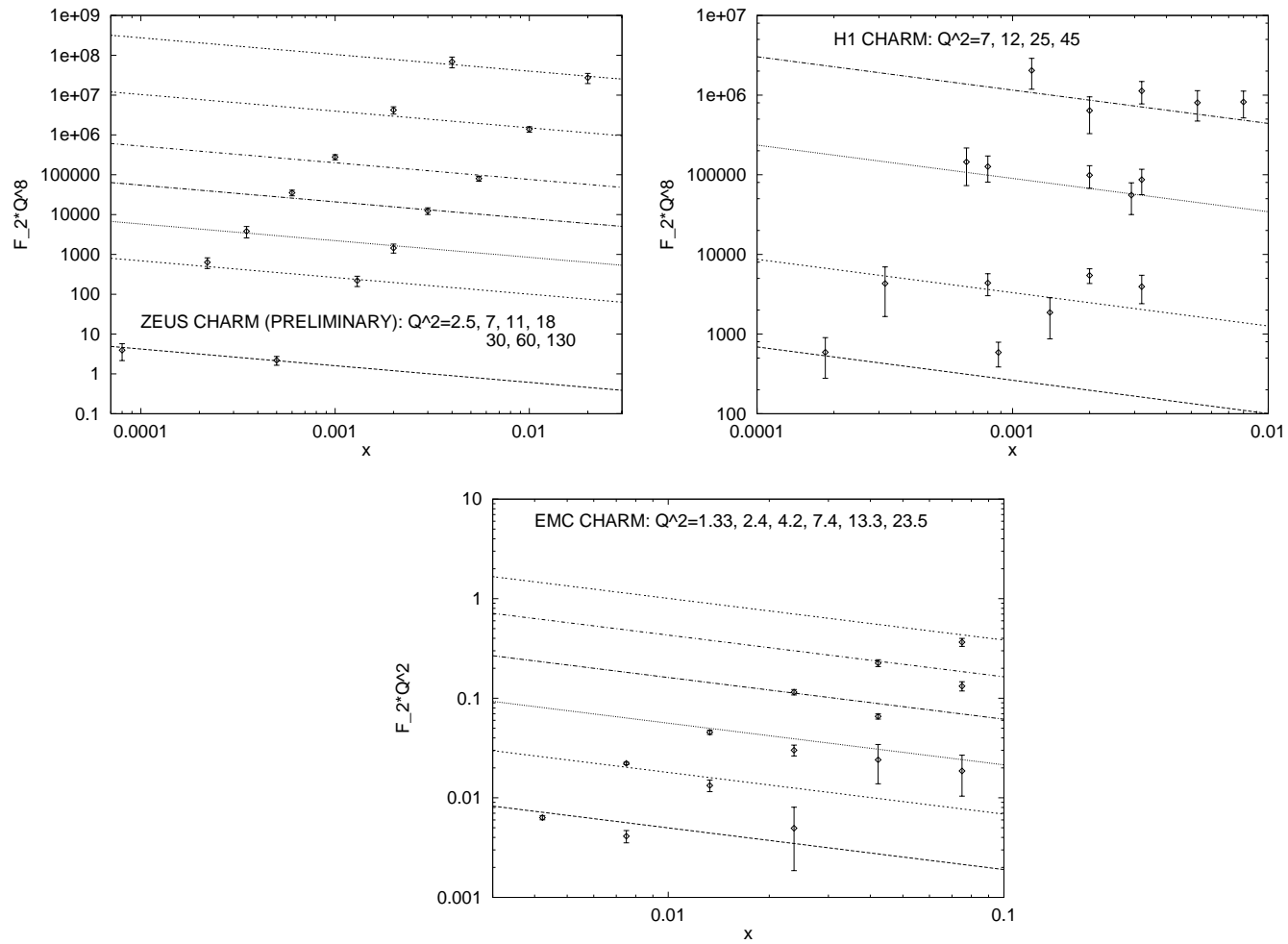


Figure 6: Fits to data for  $F_2^{c\bar{c}}$ . The vertical scales are  $Q^8 F_2$  for the ZEUS and H1 data, and  $Q^2 F_2$  for EMC, so the smaller  $Q^2$  values are at the bottom for each plot. For the comparison with EMC data, we have scaled the fit by a factor 0.5.

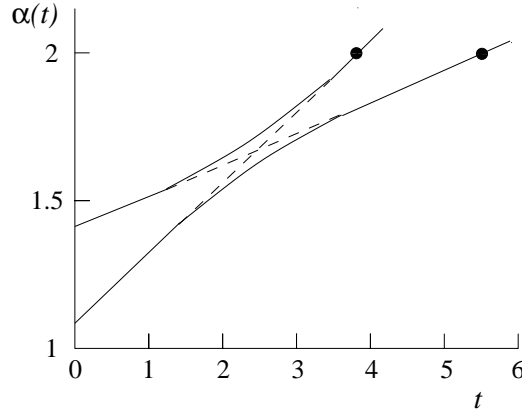


Figure 7: Conjectured soft and hard pomeron trajectories, with  $2^{++}$  glueball candidates<sup>[19][20]</sup>

enough  $Q^2$ . Assuming that so far  $Q^2$  is not large enough for there to be a significant contribution from  $b$  quarks, this implies that the coefficient of the logarithm in the hard-pomeron coefficient function for  $F_2^{c\bar{c}}$  is  $\frac{4}{9}/(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9})$  times that for the complete  $F_2$ :

$$A_C X_C = 0.4 A_0 X \quad (11a)$$

Then, the 3-parameter fit to the ZEUS data yields

$$A_C = 0.184 \quad a_C = 8.45 \quad X_C = 0.431 \quad Q_C^2 = 212 \quad (11b)$$

and is shown in figure 6. This figure also includes comparison of the fit to the earlier H1 and EMC data<sup>[15]</sup>. In the case of the EMC data, we have had to renormalise our fit with a constant factor 0.5 to get good agreement. We cannot understand why this should be, but the latest MRS fit<sup>[16]</sup> similarly is twice as large as the low- $x$  EMC charm data. Ideally, one would first make a fit to the charm-quark data, then subtract it from the complete  $F_2$  and make another fit to just the light-quark contribution, but this must wait until the data improve. Eventually, the charm data will be important for reducing the error on the value of the hard-pomeron power  $\epsilon_0$ : taken literally, the present charm data suggest that it should be towards the upper end of the range  $0.42 \pm 0.05$  that we have quoted above.

8. We have found that we need a “hard-pomeron” term, with Regge intercept about 1.4. It is perhaps ironic that we reach this conclusion just as the hard BFKL pomeron seems to be in retreat<sup>[17]</sup>. This does not rule out the possibility that our hard pomeron is perturbative. After all — as we have consistently maintained<sup>[18],[11]</sup> — in the BFKL context asymptopia is very far away from present physics. Whatever the explanation of the hard pomeron, it is interesting that the mass scale  $a_0$  that determines how rapidly its contribution to  $F_2$  rises with  $Q^2$  is considerably larger than the corresponding soft-pomeron scale  $a_1$ . Nevertheless, it may well be that even the hard pomeron is nonperturbative and that it is just a glueball trajectory. There is already some experimental support for the notion that this is true for the soft pomeron: the  $2^{++}$  glueball candidate<sup>[19]</sup> at 1926 MeV is at just the right mass to lie on a straight trajectory of intercept close to 1.08 and slope  $0.25 \text{ GeV}^{-2}$ . Another  $2^{++}$  glueball candidate has just been announced<sup>[20]</sup>, with a mass 2350 MeV. Let us suppose that this lies on the hard pomeron trajectory, and that this is also straight. The hard and soft pomeron trajectories will apparently then intersect in the complex angular momentum plane; however it is likely\* that mixing will rather cause them to avoid each other in the way shown in figure 7. This picture gives the hard-pomeron trajectory a slope close to 0.1 — though we caution that figure 7 should not be taken too seriously.

9. Although data for quasi-elastic  $\rho$  photoproduction are well described by soft pomeron exchange, this is not the case for  $J/\psi$  photoproduction. Not only is there a much more rapid rise with increasing

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\* We are grateful to Peter Collins for a correspondence about this.

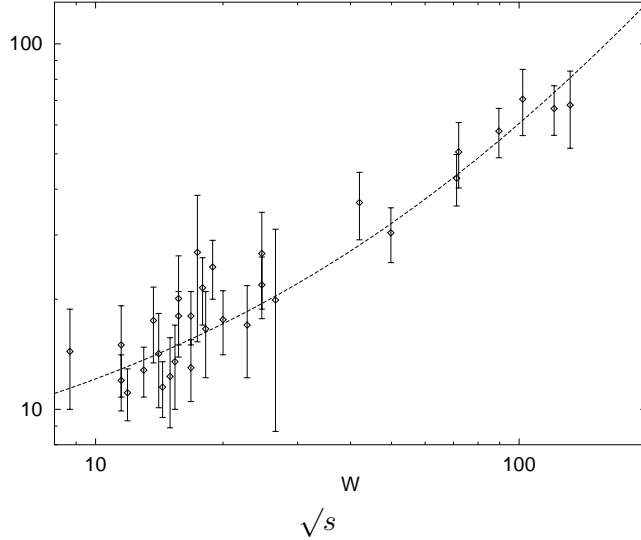


Figure 8:  $\sigma(\gamma p \rightarrow J/\psi p)$  in microbarns, together with simple fit

energy<sup>[21]</sup>, but also there is much less shrinkage of the forward peak<sup>[22]</sup>. This second feature suggests that the slope of the hard pomeron's trajectory may be small, at least near the forward direction, as we have indeed shown in figure 7. Assuming this, the contribution to the amplitude from the exchange of the two pomerons would be of the form

$$T(s, t) = i \sum_{i=0}^1 B_i(t) s^{e_i(t)} e^{-\frac{1}{2} i \pi e_i(t)}$$

$$e_0(t) = \epsilon_0 + 0.1t \qquad e_1(t) = \epsilon_1 + 0.25t \qquad (12a)$$

The functions  $B_i(t)$  include products of the form factors that couple the pomerons to the proton and the  $\gamma J/\psi$  vertex. We model them with the functions

$$B_i(t) = B_i(0) e^{2t} \qquad (12b)$$

though their exact shape is not critical for our analysis – it has just a small effect on the energy dependence. The best fit to the existing data has

$$B_0(0)/B_1(0) = 0.05 \qquad (12c)$$

and is shown in figure 8. It is interesting that H1 has new preliminary data points at higher energies<sup>[23]</sup> which agree well with our fit and confirm that the curve really should be concave upwards.

10. An obvious question is whether the hard pomeron contributes also to purely soft processes. There is perhaps a hint of a small contribution to exclusive  $\rho$  photoproduction, in that the  $t$ -slope seems to be slightly smaller than what purely soft-pomeron exchange would give<sup>[23]</sup>. The contribution of the soft pomeron to the  $pp$  and  $\bar{p}p$  total cross-sections was already fixed rather accurately<sup>[24]</sup> by the data up to ISR energies, but there is room for some extra contribution in the higher-energy data. With some small downwards adjustment of the soft-pomeron term, one can tolerate a hard-pomeron contribution of perhaps

$$0.01 s^{\epsilon_0} \qquad (13)$$

This would give slightly better agreement with the UA4 measurement than we had before<sup>[25]</sup> but would still favour the E710 measurement over that of CDF<sup>[26]</sup>.

11. The coefficient of the hard-pomeron term (13) in the  $pp$  total cross section is more than 2000 times smaller than for the soft-pomeron term. However, if it turns out that (9) is the correct  $Q^2 \rightarrow 0$  extrapolation, then in the  $\gamma p$  total cross section the ratio is an order of magnitude larger. This would support the viewpoint of those<sup>[27]</sup> who have maintained that the  $\gamma p$  total cross section contains a significant piece that is different in character from purely hadronic cross sections. This additional piece cannot factorise in the Regge sense, because it would give a  $\gamma\gamma$  total cross section much larger than has been measured<sup>[28]</sup>. However, the preliminary OPAL and L3 data do hold the prospect that the hard pomeron may be visible in  $\gamma\gamma$  collisions.

12. The main message of this paper has been that Regge theory is applicable even at very large  $Q^2$ , if only  $x$  is small enough. In this, our work does not relate immediately to any of the many other fits in the literature: we insist that the hard pomeron is present already at small  $Q^2$  and that  $Q^2$  evolution keeps both it and the other Regge powers intact. Kerley and Shaw<sup>[13]</sup> also have two pomerons, though the details of their work are very different. Our approach is in the same spirit as that of Haidt<sup>[29]</sup>, though the details are again very different. The work of Nikolaev, Zakharov and Zoller<sup>[30]</sup> is closest to ours, though they do not extend their fit below  $Q^2 = 1.5$  and therefore have rather different powers of  $x$  from ours. Like us, they find that the coefficient functions of the nonleading  $x$  powers peak somewhere around  $Q^2 = 10$ , though their behaviour at large  $Q^2$  is very different from ours. Indeed, we suggest that the soft pomeron contribution, although large for  $Q^2$  as large as 10 or more, is probably higher twist.

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