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SOFT HADRON REACTIONS

P V LANDSHOFF
*CERN, Geneva**

ABSTRACT

A wide variety of experimental data are described in terms of the exchange of an object called the pomeron. Its exchange controls total hadronic cross-sections, elastic scattering and diffraction dissociation. Its phenomenology is surprisingly simple and has resulted in several successful predictions. Among these are the size of the total cross-section and the shape of the forward elastic-scattering peak at Tevatron energy, and the pomeron structure function recently measured at the CERN collider. A model based on the exchange between quarks of a pair of nonperturbative gluons provides the beginnings of an understanding of the pomeron's simple properties.

1. Introduction

My talk is about the long-range strong interaction at high energy. Its phenomenology is surprisingly simple and is described by the exchange between quarks of an object known as the pomeron. This allows a very economical description of a wide variety of data, which include

- Total cross-sections for $pp, \bar{p}p, \pi p, Kp, pn, \bar{p}n, \pi n, Kn$ and γp scattering
- The forward peak in pp and $\bar{p}p$ elastic scattering
- Diffraction dissociation
- νW_2 at small x

Furthermore, the pomeron has a structure function, just as if it were a hadron or a photon[1].

It is a difficult but very interesting theoretical problem to understand why the phenomenology of pomeron exchange should be so simple. It is now rather sure that pomeron exchange occurs between single quarks[2] and is just gluon exchange.

*On leave from DAMTP, University of Cambridge

TALK AT QCD : 20 YEARS LATER (Aachen, June 1992)

The simplest approximation to it is the diagram of figure 1. Notice, though, that this is only an approximation and so it has to be used with care and intelligence; for example figure 1 gives no variation with the energy s and so a Regge factor $s^{\alpha(t)-1}$ has to be added by hand.

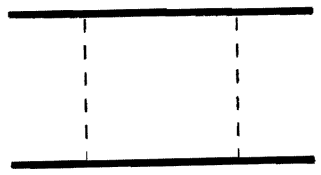

Figure 1
Exchange of nonperturbative gluons between quarks

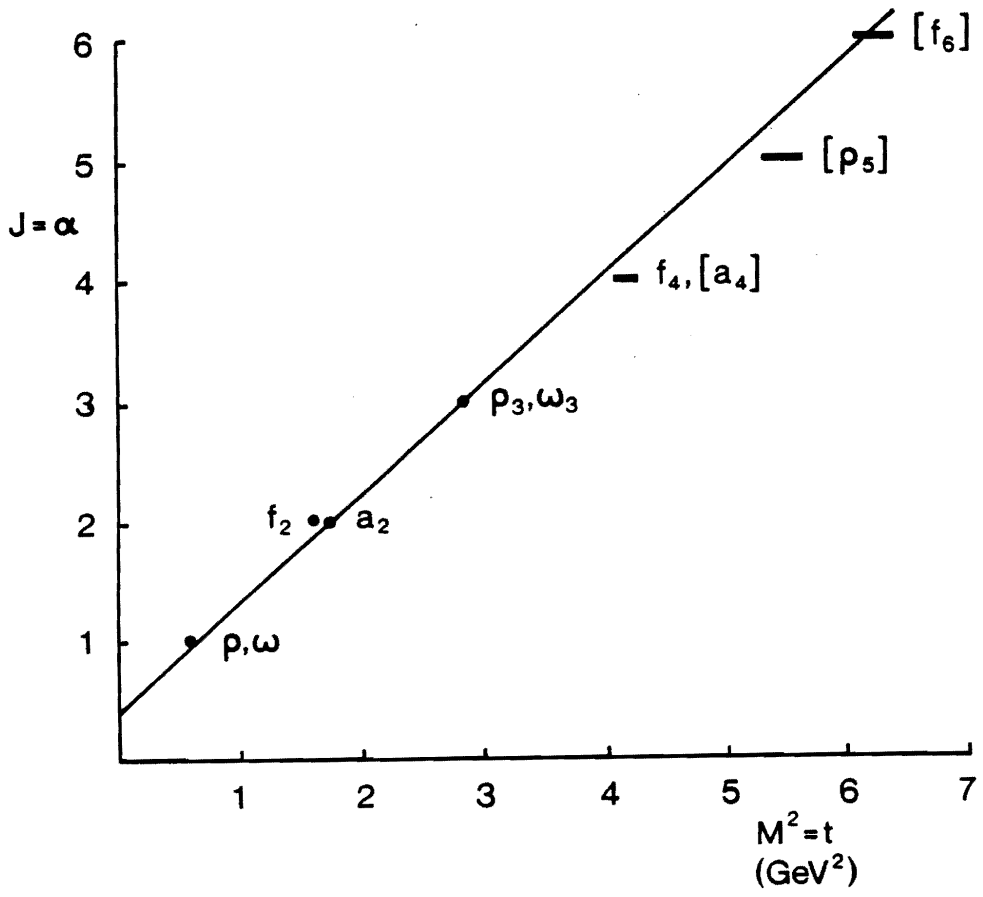

Figure 2
Regge trajectory: particle spins α plotted against their squared masses t

Figure 1 approximates well to experiment only if the gluons that are ex-

changed have propagators that are nonperturbative[3]. Thus pomeron exchange is a nonperturbative mechanism. Recently, there has been a lot of interest in the possibility that there might be also a purely perturbative pomeron[4]. If this does exist it should become apparent in semi-hard processes. So far, however, experiment has not revealed it, and the processes I shall talk about are all controlled by nonperturbative pomeron exchange.

2. Total Cross Sections

Figure 2 shows a plot of the spins α of the particles ρ, ω, f_2, a_2 and their excitations, against their squared masses t. The particles in square brackets are listed in the data tables, though there is some uncertainty about them. The straight line has equation

$$\alpha(t) = 0.44 - 0.93t \tag{1}$$

In the early 1960's, there was developed Regge theory[5], which relates $\alpha(t)$ to the high-energy behaviour of scattering amplitudes. The line is extrapolated down to negative t, so that t may then be regarded as a momentum-transfer variable. Then the exchange of all the particles associated with $a(t)$ (see figure 3) gives an elastic scattering amplitude a behaviour at high centre-of-mass energy $\sqrt{s}$

$$T(s,t) \sim \beta(t) s^{\alpha(t)} \xi_{\alpha(t)} \tag{2a}$$

Here $\beta(t)$ is an unknown real function, while

$$\xi_{\alpha(t)} = \begin{cases} e^{-\frac{1}{2}i\pi\alpha(t)} & \text{C=+1} \\ ie^{-\frac{1}{2}i\pi\alpha(t)} & \text{C=-1} \end{cases} \tag{2b}$$

where C is the C-parity of the exchanged particles. Thus the "Regge trajectory" $\alpha(t)$ determines both the power of s and the phase.

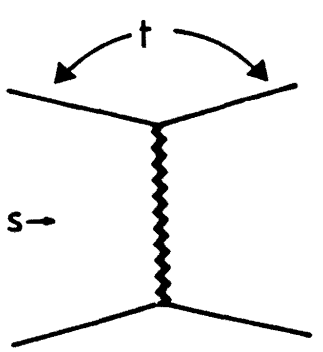

Figure 3
Reggeon exchange

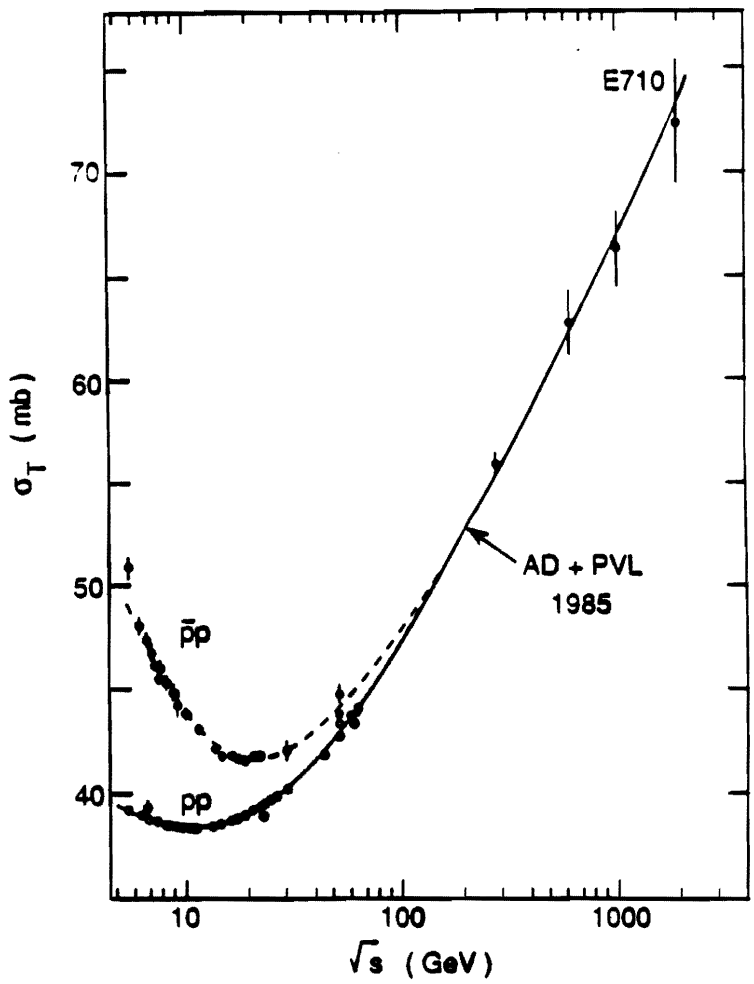

Figure 4
$\bar{p}p$ and pp total cross-section data. The curve is the 1985 prediction of reference 1

The optical theorem relates any total cross section to s^{-1} times the corresponding forward elastic scattering amplitude. The difference between pp and $\bar{p}p$ scattering recieves contributions only from $C = -1$ exchange in the t channel, that is from ρ and ω exchange. So from (1) and (2) we expect the difference between these total cross sections to behave as $s^{0.44-1} = s^{0.56}$. Figure 4 shows data for the pp and $\bar{p}p$ total cross-sections. The curves in the figure correspond to[2]

$$\sigma(\bar{p}p) - \sigma(pp) = 70s^{-0.56} \tag{3a}$$

The average of the cross sections receives only contributions from $C = +1$ exchange. We expect to see the same power of s coming from the f and the a, because according to figure 2 they lie on the same trajectory $\alpha(t)$ as the ρ and the ω, but evidently

we need something else in order to reproduce the rise in the data at large s. The curves in figure 4 have this rising component as a very slowly varying power:

$$\tfrac{1}{2}[\sigma(\bar{p}p) + \sigma(pp)] = 105s^{-0.56} + 22.7s^{\epsilon} \tag{3b}$$

where

$$\epsilon \approx 0.08 \tag{3c}$$

As I shall explain, there is reason to believe that most of the rising component corresponds to a Regge pole, that is it is a simple power of s, with a trajectory which is to a good approximation linear, like the trajectory in figure 2. This trajectory, which has quantum numbers $C = +1$ and isospin 0, is called the pomeron trajectory. It corresponds to

$$\alpha(t) = 1 + \epsilon_0 + \alpha' t \tag{4a}$$

where

$$\epsilon_0 = 0.086$$

$$\alpha' = 0.25\text{GeV}^2 \tag{4b}$$

The reason that ϵ in (3) varies with s is that the term s^{ϵ} represents a mixture of effects. At present energies the main [illegible]s single-pomeron exchange, which according to (4) behaves like $s^{0.086}$. The power closer to 0.08 is obtained by adding in double-pomeron exchange, which is negative and at CERN collider energy decreases the total cross-section by probably about 10%. At higher energies the contribution from double-pomeron exchange will become relatively larger. Eventually, one will also have to take account of the exchange of more than two pomerons (though up till now this seems to be unimportant), until at asymptotic energies an effective power s^{ϵ} is not a good representation and instead the Froissart bound $\log^2 s$ is saturated.

That a power close to 0.08 gives a good description of rising total cross sections was realised by Cheng, Walker and Wu[6] already in the early 1970's. However, even now these authors, and many others, do not accept that the pomeron corresponds to a simple Regge pole[7], though I shall explain that there is good reason to believe that indeed it is.

The value 0.25 for the slope α' was extracted from the then available data already in 1973 by my student Jaroskiewicz[8] and is now known rather accurately: I would guess that the error on it is less than ± 0.01. Likewise, the error on ϵ_0 is now quite small, perhaps ± 0.002. An interesting question is whether any particles will be found on the trajectory. If it remains straight for positive t, the lightest such particle will be a 2^{++} state at about 1900 MeV. If indeed pomeron exchange is nothing but gluon exchange, one would expect this particle to be a glueball.

Many authors prefer to believe that the rising component of total cross sections corresponds to logarithmic terms rather than a power. This is because of a belief that the Froissart bound provides a constraint on data even at present energies, though it was pointed out already long ago by Collins and Gault that this belief is false[9] because numerically the bound is about 10 barns at CERN collider energies, far above the measured values. It is amusing that parametrisations[10] based on a belief that the Froissart bound *is* relevant at present energies yielded a much higher prediction for the total cross section at the Tevatron, and parametrisations involving $\log^2 s$ no longer seem appropriate in the light of the Tevatron measurement[11].

Notice that the same steadily-rising component s^ϵ is present in the data of figure 4 all the way from $\sqrt{s} = 5$ GeV to $\sqrt{s} = 1800$ GeV. This is remarkable, when one realises that all sorts of things are produced at 1800 GeV, particularly minijets, which cannot be produced at 5 GeV. The total cross-section does not notice this new production and is smooth: as new final states come in, old ones are correspondingly reduced.

Fits exactly similar to (2) may be applied to all other total cross-sections. The Landolt-Börnstein series[12] gives fits to each total cross section with 5 parameters

$$A + BP^N + C\log^2 P + D\log P \tag{5a}$$

where P is the beam momentum. This parametrisation has no theoretical basis and the values of their parameters vary wildly from one reaction to another. For example, $N = -7.8$ for π^+p but -1.4 for π^-p. But it provides excellent numerical representations of the data. I have made fits to their fits, with the same parametrisations as in (2): for each pair AB and $\bar{A}B$ of total cross sections I assumed

$$Xs^{0.08} + Ys^{-0.56} \tag{5b}$$

with the same value of X but different Y, that is 3 parameters for two cross sections. In this way, I obtained fits to within 1% for $\sqrt{s} > 5$ GeV ! Further, $X = 23.0$ for $\bar{p}n$ and pn, remarkably close to the 22.7 for pp and $\bar{p}p$ given in (2), as it should be if the pomeron really has the quantum numbers of the vacuum and so is blind to the isospin of the nucleon. For $\pi^\pm p$, I found $X = 14.0$. It is significant that the ratio 14/22.7 of the s^ϵ terms is very close to 2/3. This is a sign that the pomeron couples to single valence quarks in a hadron (the additive quark rule). For $K^\pm p$, $X = 12.1$, which seems to imply that strange quarks scatter more weakly:

$$\sigma(su) \approx 0.7\,\sigma(uu) \tag{6}$$

However, it may be that the apparent relative weakness of the strength of the pomeron to heavier quarks is not to be attributed to the intrinsic strength of the coupling, but rather is a radius effect, to be blamed on the radius of hadrons containing heavier quarks being smaller than those composed just of light quarks[13,14,15].

Incidentally, the γp total cross section data also are well parametrised by a form (5), with $X = 0.07$. Thus one expects 170 μb at $\sqrt{s} = 250$ GeV, soon to be tested at HERA. Other predictions have been much higher[16].

The weak feature of Regge theory is that, while the exchanges of single Regge poles usually provide quite a good description of experimental data, to be more accurate one must include double exchanges. We have never learnt how to calculate these unambiguously, though their qualitative properties are known[5]. I have mentioned that the two-pomeron exchange contribution to the total cross section is negative: this is sure, but less sure is my estimate that its magnitude is about 10% of the single exchange. People often use a geometrical approach to this problem, known as the eikonal model, but it has to be recognised that this is only a model and almost certainly is wrong, since it does not take account of correlations among hadron constituents. We do not know how large these correlations are. Worse than that, implementations of the eikonal model often do not respect crossing symmetry, and therefore do not give the amplitude the correct phase. This is particularly serious when the model claims to reproduce the dips seen in elastic scattering, since the generation of dips is particularly delicate and the correct phase is all-important[2].

3. Elastic Scattering

When one considers all the available data for total cross-sections, elastic scattering and diffraction dissociation, the following phenomenological facts about the pomeron become apparent[2]

- It couples to single quarks
- It is a simple Regge pole.
- It is rather like a $C = +1$ isoscalar photon

The first of these properties is tested not only by the validity of the additive quark rule for total cross sections, but also more directly in ISR data[17] for certain diffraction dissociation processes. Theoretically, it is difficult to imagine how one can have the pomeron coupling to single quarks without its being a simple Regge pole. Further evidence that it is a simple Regge pole comes from a property known as factorisation. This property says that figure 3 factorises into a product of a vertex associated with the coupling of the exchanged Regge pole to each of the two hadron lines, times the "reggeon propagator" $s^{\alpha(t)}\xi_{\alpha(t)}$; that is, the function $\beta(t)$ in (2) factorises. This factorisation has been tested most directly[18] in diffraction dissociation (figure 5): if the differential cross section for a beam of type A to smash a proton up is divided by the corresponding elastic differential cross section, the result is independent of A.

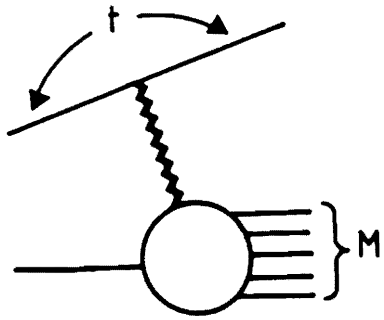

Figure 5
Diffraction dissociation by pomeron exchange

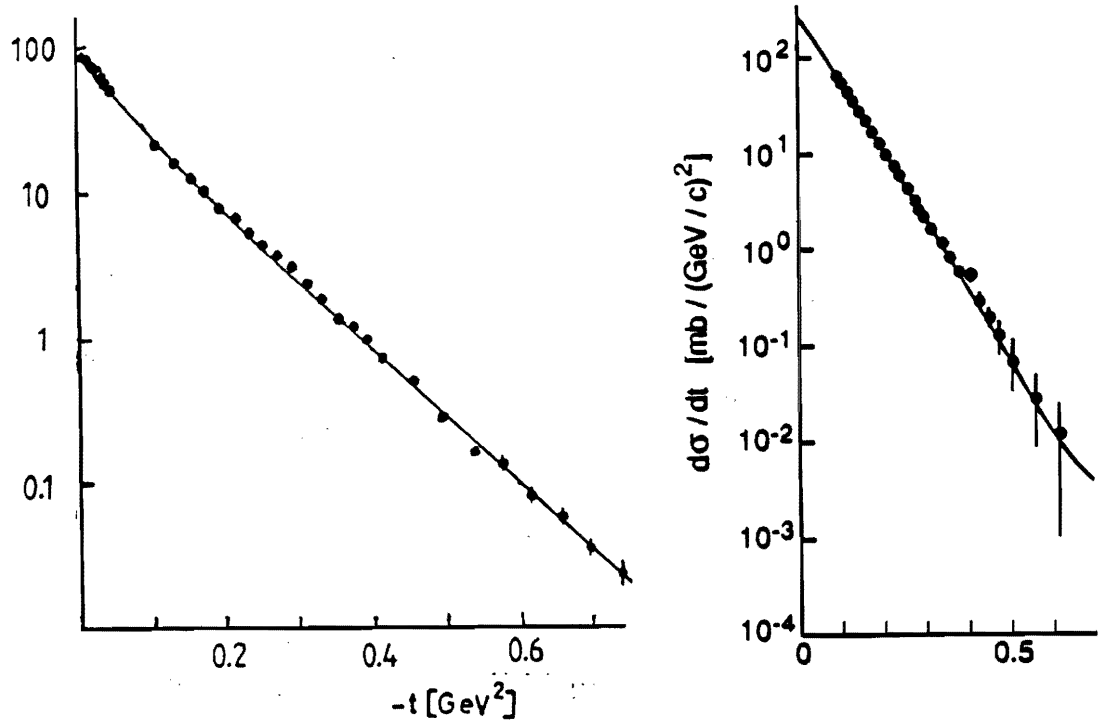

Figure 6
$\sqrt{s}$ = 53 GeV ISR data for pp and $\sqrt{s}$ = 1800 GeV E710 data for $\bar{p}p$ elastic scattering with 1985 curves of reference 1

The property that the pomeron resembles a $C = +1$ isoscalar photon is tested in elastic scattering. Just as the coupling of the photon to a proton involves a Dirac form factor, so will the coupling of the pomeron. So single pomeron exchange

contributes to pp or $\bar{p}p$ elastic scattering

$$\frac{d\sigma}{dt} = \text{constant } [F_1(t)]^4 s^{2\alpha(t)-2} \tag{7}$$

For want of any better knowledge we take the same isoscalar form factor $F_1(t)$ as has been measured in eN scattering, and this seems to work well:

$$F_1(t) = \frac{4m^2 - 2.8t}{4m^2 - t}\left(\frac{1}{1 - t/0.7}\right)^2 \tag{8}$$

This corresponds to dipole G_M, and G_M/G_E scaling. Many authors assume rather that the form factor should be G_M, but I have never understood why and it does not work nearly as well. (There is no contribution from the other Dirac form factor $F_2(t)$, because this form factor is small in the isoscalar channel.) In order to compare with data we have to add in to (7) the correction corresponding to two-pomeron exchange, which I have said is relatively small at small t, though less so at larger t, particularly at higher energies. Comparing the result with very-small-t data at $\sqrt{s} = 53$ GeV determines α', and we then have an excellent fit to all ISR data out to values of $|t|$ of about 0.7. The same fit[2] with no adjustment since 1985 to the small number of parameters, correctly describes the recent Tevatron data[19] (figure 6). This is something of a triumph for Regge theory, which correctly predicted the change of exponential slope of about 3.5 units compared with ISR energies. Single-pomeron exchange gives a change of slope equal to $\Delta(2\alpha' \log s)$, though there is a small correction because of the two-pomeron exchange.

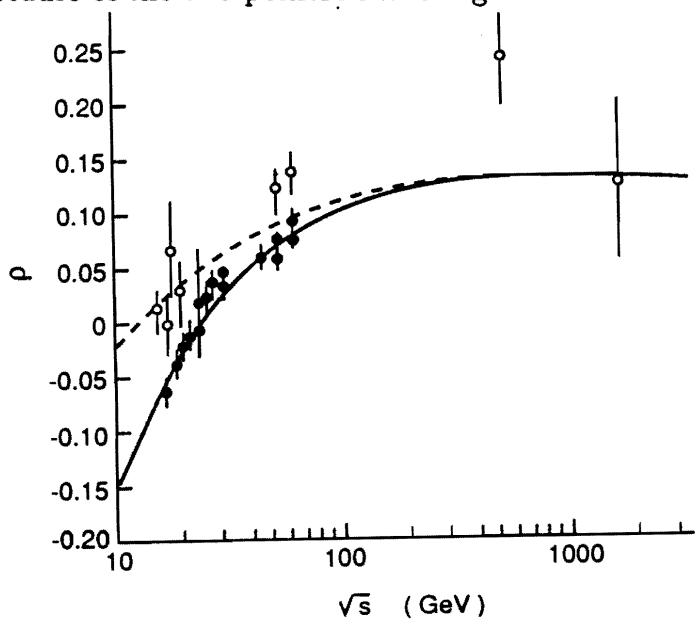

Figure 7
Data for the ratio of the real part of the pp and $\bar{p}p$ forward elastic scattering amplitudes with typical theoretical expectation

I stressed that Regge theory links the phase of an elastic amplitude at each t to its variation with energy at that t. In fact this relationship is much more general than Regge theory[5]. Figure 7 shows data for the ratio of the real part of the forward amplitude to its imaginary part, together with a plot of the theoretical expectation. The UA4 measurement is being repeated; if the new measurement still does not lie on the curve, something rather new will have been discovered.

4. Pomeron Structure Function

Diffraction dissociation is the name given to inelastic events in which one of the initial hadrons changes its momentum by only a very small amount. In doing so, it 'radiates' a pomeron. The other initial hadron is hit by the pomeron and breaks up into a system X of hadrons. The UA8 experiment at the CERN collider[20] has measured the angular distribution of the energy flow of the particles that make up the system X, in its rest frame, that is in the centre-of-mass frame of the pomeron-hadron collision. This is shown in figure 8. for events where the pomeron takes only a fraction 0.006 of the initial mo[illegible]n of the initial hadron from which it was radiated. This corresponds to an invariant mass of 50 GeV for the system X. Notice the vertical logarithmic scale: there is a huge forward peak. The pomeron has hit the other initial hadron hard and knocked most of its fragments forward. In this respect it behaves as if it were itself a hadron, or a photon.

In fact, as I have already said, it is useful to think of the pomeron as resembling a $C = +1$ isoscalar photon. One cannot take this analogy too far; for example, there is no such thing as a pomeron *state*, the pomeron can only be exchanged. However, one can define its structure function[1]

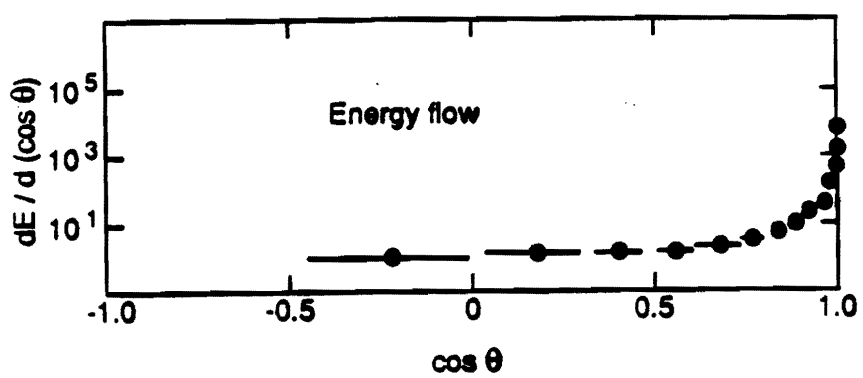

Figure 8
UA8 data for energy flow in diffraction dissociation, in the rest frame of the system X of fragments of the shattered hadron.

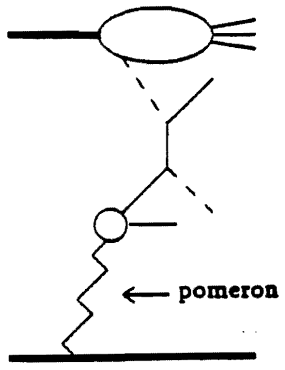

Figure 9
Diffractive high-p_T jet production mechanism

This is measured from events where the system X has resulted from a hard collision, for example when it contains high-P_T jets. Given that, as we have seen, the pomeron couples to quarks, it is natural to suppose that the corresponding diagram for this reaction is that of figure 9, where one of the quark lines at the pomeron vertex suffers a hard collision with a gluon from the other initial hadron and so produces a pair of high-p_T jets. If we forget the initial hadron from which the pomeron radiated, it is as if the pomeron were an initial particle, and then one would calculate such a diagram by introducing its structure function. We predicted[21] that, for each light quark and antiquark to which the pomeron couples, its structure function is

$$xq_{\text{pomeron}} = \tfrac{1}{3}C\pi x(1-x) \tag{9}$$

where the constant C is determined by measuring the small-x behaviour of the quark distribution in a proton:

$$xq(x) \sim Cx^{-\epsilon}$$

so that $C \approx 1/6$. Just as the photon structure function has a piece at small x that is calculated from vector dominance, so the pomeron structure function also has an additional piece, but this is important only for very small x and for most purposes (10) is sufficient[21]. If we sum (10) over the light quarks and antiquarks,

$$xq_{\text{pomeron}} \approx 0.8x(1-x) \tag{10}$$

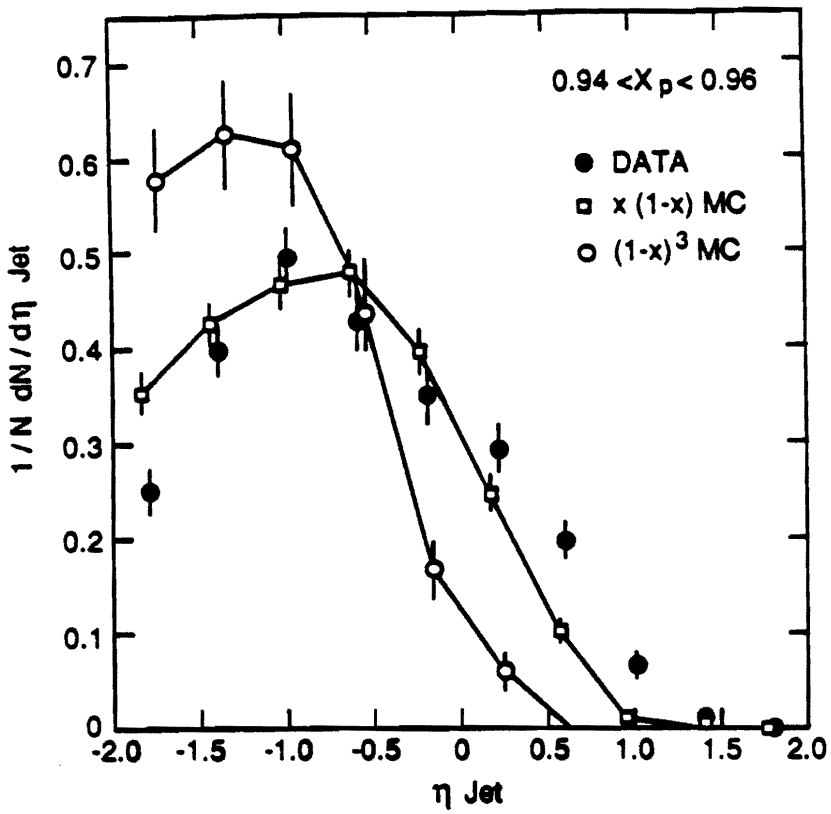

Figure 10
UA8 data for pseudorapidity distribution of $p_T > 8$ GeV jets produced in diffraction dissociation, with expectations for two different choices of the shape of the pomeron structure function

UA8 has studied the shape of the pomeron structure function, by looking at events where the sytem X contains jets with $p_T > 8$ GeV and the pomeron takes about 5% of the momentum of its parent hadron. Figure 10 shows their raw data[22], compared with the result of subjecting two guesses for the shape of the pomeron structure function to a Monte Carlo that simulates the acceptance of their apparatus. Evidently the shape $x(1-x)$ works well, much better than $(1-x)^5$. It does not fit perfectly — I will come back to this in a minute — but UA8 go on to determine the coefficient that the data require for $x(1-x)$. This depends on whether the structure function is dominantly a quark one, as we suppose, or a gluon one. UA8 are not able to distinguish the two possibilities from their data. If quark, the coefficient is 0.8, as predicted in (10). If gluon, it is less than half this, because gluons are more efficient than quarks in producing high-p_T jets. The experimental error on the coefficient is quite large, perhaps 50%, but one can certainly exclude the coefficient 6 which would be obtained by supposing that a pomeron is so much like a hadron that its structure function obeys a momentum sum rule.

It is important to determine whether the pomeron structure function is indeed predominantly quark rather than gluon. There has been some confusion about this. The fact that, as everybody agrees, pomeron exchange is gluon exchange, does not imply that the structure function is entirely, or even predominantly, gluonic. What matters is what the pomeron prefers to couple to. While we cannot exclude that it couples to gluons, there is certainly an important coupling to quarks, otherwise we should not have the additive-quark rule for total cross-sections. We have argued that the quark coupling in fact dominates, though there is some uncertainty about this and further experiment, particularly at HERA, is needed to decide the matter. Because virtual photons couple to quarks, HERA will measure the quark structure function directly.

Let me return now to the small discrepancy between the raw data in figure 10 and the output from the $x(1-x)$ assumption. UA8 have confirmed that the discrepancy is indeed a real one, by looking at those events in which they see both of the high-p_T jets. They find that the two-jet system can take all, or nearly all, the energy of the parton/pomeron collision; that is, in some events there is little or no energy to spare for any spectator fragments from the pomeron structure. In figure 9 there is one such spectators. One can also draw a diagrams in which this second quark is actually the recoil high-p_T jet, instead of being a spectator. An example is drawn in figure 11.

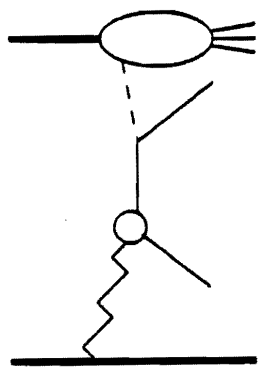

Figure 11
Alternative mechanism for diffractive high-p_T jet production

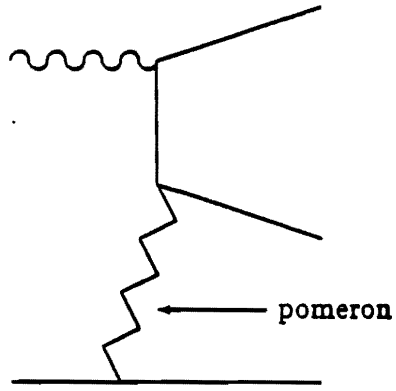

Figure 12
Mechanism for HERA events where the proton loses only a small fraction of its momentum, with all the remaining energy going into a pair of high-p_T jets

It is consistent to suppose that figure 11 is responsible for the discrepancy that UA8 find, but this is not certain. It will therefore be interesting to look for such a mechanism directly at HERA. The diagram is drawn in figure 12, where now we are considering the case of a real initial photon. In the final state, there is only the initial proton and a pair of high-p_T jets. In the gluon-exchange model, figure 12 corresponds to four diagrams. Our calculation of these[23], for $\sqrt{s_{\gamma p}} = 250$ GeV and $p_T^{\rm JET} > 5$ GeV, gives a cross-section $\sigma^{\gamma p} \approx 1$ nb.

5. Theory

The pomeron that has been seen in data is the soft, or nonperturbative, pomeron. Its phenomolgical properties are summarised at the beginning of section 3. The other pomeron in the literature[4], the Lipatov or perturbative pomeron, displays none of these phenomenological properties. It does not couple to single quarks. When $s \to \infty$ its behaviour is not that of a simpkle Regge pole, that is its contribution is not a simple power of s, and it increases much more rapidly than $s^{0.08}$. However, subasymptotic corrections are very important for the perturbative pomeron[24], and for present values of s it corresponds to a sequence of quite widely-spaced simple Regge poles. As $s \to \infty$ these simple Regge poles coalesce, until ultimately there is no simple pole. Although so far there is no trace of the perturbative pomeron in total cross sections, it is possible[25]that it will appear at higher energies, as shown in figure 13.

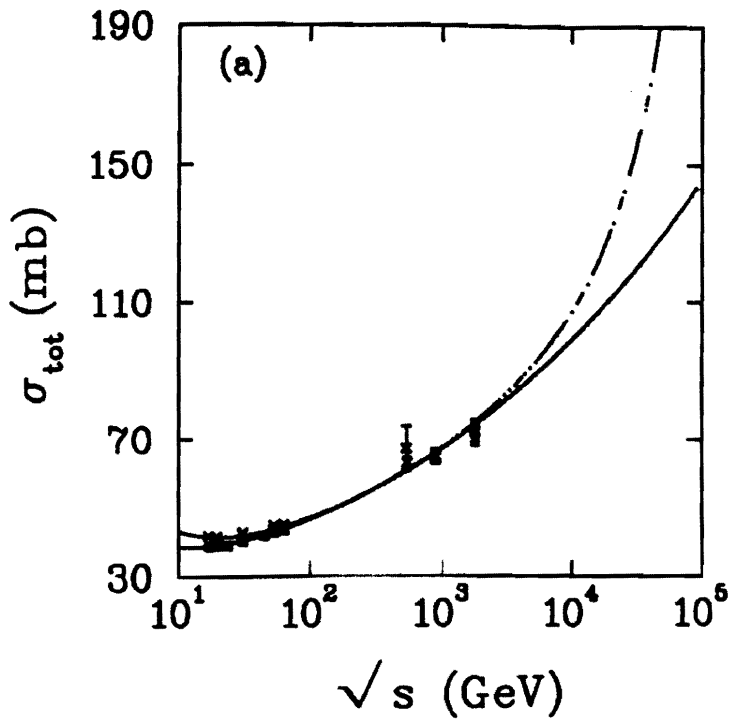

Figure 13
Possible faster rise of the total cross section at high energy

Meanwhile, the great simplicity of the properties of the nonperturbative pomeron needs explaining. I have said that an approximation to pomeron exchange is the two-gluon-exchange diagram of figure 1. However, the gluons must be nonperturbative[26], otherwise there is no factorisation and no additive quark rule. What is needed is that the gluon propagator $D(k^2)$ should not have a pole at $k^2 = 0$, so that the integral

$$I = \int_{-\infty}^{0} dk^2 \, [g^2 D(k^2)]^2 \tag{11}$$

converges[4]. Some authors[13,27] achieve this by giving the gluon a mass. However, I believe that the gluon propagator should not have a real pole at all, because such a pole would correspond to the propagation of a particle through arbitrarily large distancer, which is prevented by confinement. There have been several attempts to discover the effect of confinement on the propagator. For example, by completely different methods two sets of authors[28] arrive at

$$D(k^2) = \frac{k^2}{k^4 + m_0^4} \tag{12}$$

which even vanishes at $k^2 = 0$. Other authors[29] find more complicated forms, with

cuts rather than poles. Fortunately, to make progress with the theory of the soft pomeron, the precise form of the gluon propagator does not matter too much, so long as the integral (11) converges. As soon as one tries to depart from perturbation theory, there are big problems with gauge invariance. While there have been some interesting attemps to set up a gauge-invariant formalism[15,30], inevitably one must approximate to get any output to one's equations. Most people find it simpler to work in a definite gauge[7,31,32], usually the Feynman gauge. If $D(k^2) \neq 1/k^2$, there is necessarily a fixed length scale a in order that D may have the correct dimension. One may think of this as the maximum distance that confinement allows a gluon to propagate, or as a correlation length of the gluon condensate in the QCD vacuum. The data need $a \approx 1$ GeV^{-1}, and it is interesting that a recent lattice calculation[33] obtains a similar value. With such a value, $a^2 \ll R^2$, where R is the radius of a light hadron. Two consequences of this are[4]:

(i) When a pair of gluons couple to the quarks in a hadronic bound state, they prefer both to couple to the same quark, as is necessary if one is to obtain the additive quark rule in a simple way

(ii) The exchange of a pair of gluons between quarks (figure 1) at large s has the effective structure

$$\beta_0^2 \gamma^\mu \dot{\gamma}_\mu \tag{13}$$

(times a signature factor which is equal to 1 for both quark and antiquark scattering). This is exactly like the exchange of a $C = +1$ photon, as favoured by experiment. The constant β_0^2 is $I/(36\pi)$, where I is the integral (11). The data require $\beta_0^2 \approx 4$ GeV^{-2}. Nearly all the contribution to the integral (11) must come from small k^2: the part of the integration with $|k^2| > 1$ GeV^2, for which the integrand may reasonably be assumed to be approximately equal to its perturbative form, contributes only about 2% of the total, so that two-gluon exchange is very much a nonperturbative phenomenon.

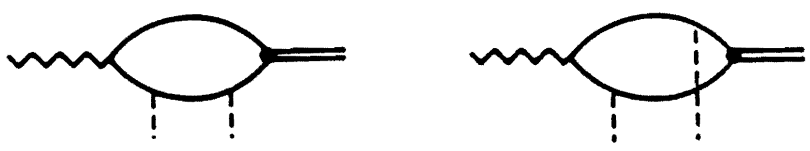

Figure 14
Couplings of two gluons to the γ–ρ vertex

It is very difficult to derive the Regge factor $s^{\alpha(t)-1}$ that should multiply (13). It must come from complicated iterations of both t-channel and s-channel insertions in figure 1. One might hope perhaps to calculate these from a Lipatov-like equation with nonperturbative gluon propagators[34], but there are big practical difficulties with such a calculation and so far the results are no more than encour-

aging.

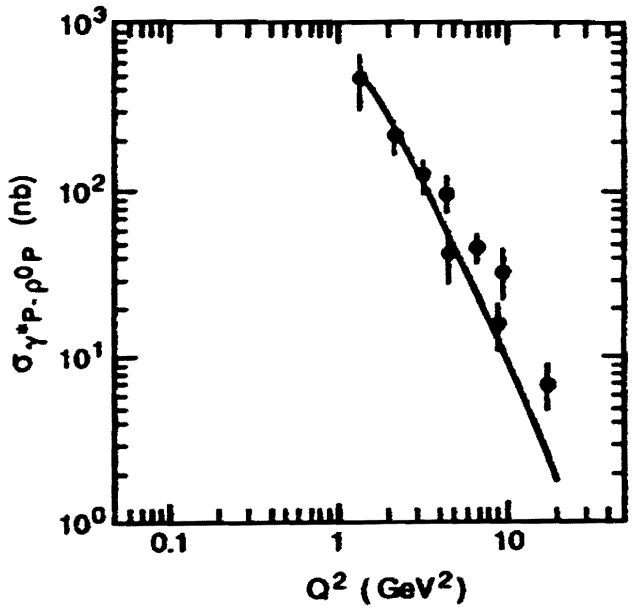

Figure 15
Cross section for $\gamma^* p \to \rho p$

An important process for testing the theoretical ideas is $\gamma^* p \to \rho p$, where the γ^* is radiated from an electron or muon beam. At high Q^2 the γ^* is converted into a ρ through the a simple quark loop, with the two gluons that make the pomeron coupled to it (figure 14). Effectively, the radius of the virtual photon is $R = 1/Q$, so that as Q^2 increases the inequality $R^2 \gg a^2$ becomes less and less true, and figure 14b becomes relatively more important. It tends to cancel figure 14a, and together the two diagrams give the amplitude a factor[31,35] $1/(a^2 Q^2)$. The data test this, and measure a: the curve in figure 15 corresponds to $a = (1.1 \text{ GeV})^{-1}$. (The data are from EMC[36]; a recent measurement by NMC[37] finds that they are to some extent contaminated at large Q^2 by inelastic events.

6. Conclusions

• The phenomenology of the pomeron is very simple. It describes a huge amount of data and has allowed several successful predictions.

• Nonperturbative QCD provides the beginnings of an explanation for this simplicity, but a complete theory will need *much* more work.

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