The Pomeron at HERA

J.Bartels

II Institut für Theoretische Physik, Universität Hamburg,
D-22761 Hamburg, Germany.

Abstract

This talk presents an overview of recent developments of the Pomeron at HERA

Résumé

Cet exposé présente une revue des récents développements concernant le Pomeron à HERA

1. Introduction: The Old Pomeron

During the last few years deep inelastic scattering (DIS) at small Bjorken-x has lead to a renaissance of interest in the Pomeron : the discovery of the new "hard Pomeron" and the observation of the rapidity gap events constitute novel elements in the study this problem, and there is no doubt that we are in the process of gaining completely new insight into QCD-dynamics of strong interactions at high energies. Since the small-x region of deep inelastic scattering region lies at the interface between hard scattering and soft (Regge) physics, the understanding of the data requires knowledge of both theoretical frameworks. In this talk I will try to discuss some of those issues of the Pomeron which are presently being investigated.

Let me begin with a very brief review of the "old" soft Pomeron. The high energy dependence of the total hadronic cross sections for pp, $p\bar{p}$, πp, Kp, and γp scattering has been found [1, 2] to be compatible with the simple formula

$$\sigma_{tot}(AB) = \beta_A(0) s^{\alpha(0)-1} \beta_B(0), \tag{1}$$

where the power of the energy s is given by the universal function (Pomeron trajectory function):

$$\alpha(t) = 1.08 + \alpha'_p t, \tag{2}$$

and the functions $\beta_A(t)$, $\beta_B(t)$ belong to the scattering particles A and B. ♯ This expression is the most straightforward prediction of Regge theory ††, and it is interpreted as describing the "exchange" of the "Pomeron" between the scattering particles A and B. Since the scattering process is elastic, the Pomeron carries the quantum numbers of the vacuum. Most striking features

* Plenary talk given at the Workshop on Deep Inelastic Scattering and QCD, Paris, April 1995

♯ An alternative description, based upon an eikonal formula, of total hadronic cross sections is contained in [3] and [4]. [3] contains, for the exponent of the energy in the eikonal, the number 0.083.

††To be more precise: Regge theory only predicts the analytic form of eq.(1). The values of the parameters β and the Pomeron trajectory function have to be measured in an experiment or, ultimately, to be derived from the underlying theory of strong interactions. Also, there are corrections to (1) due to the exchange of secondary Regge poles which at high energies are power suppressed.

of (1) are the universal, weak energy dependence of the total hadronic cross sections and the (approximate) factorization property. Writing the scattering amplitude as a Fourier transform

$$T_{el}(s,t) = \int d^2b e^{iqb} A(s,b), \quad ,t=-q^2 \qquad (3)$$

one easily sees that the region of small momentum transfer t probes large transverse distances b, i.e. the nature of the Pomeron is mainly nonperturbative. So far there is no derivation of the Pomeron from QCD.

Because of its fundamental role in high energy scattering, many attempts have been made to understand its nature. Regge theory, on the one hand, views the Pomeron as some "state" in the cross channel. In this context it is often speculated that the Pomeron lies on the Regge trajectory of a glueball state with a mass around 2 GeV^2. S-channel unitarity, on the other hand, makes it more natural to look at the Pomeron as "the shadow" of inelastic particle production, i.e. to consider the "Pomeron exchange" as a s-channel process (in space and time). In this picture [5, 6] for the elastic forward scattering of an energetic hadron A on the target particle B at rest, particle A fluctuates, i.e. with a certain probability it breaks up into a system of constituents (partons) long before it reaches B, and only the "wee" partons with very small momentum fractions interact with particle B. The energy dependence of the scattering process is given by the probability of finding wee partons inside A and the interaction cross section of the wee partons with hadron B at rest. The same process could, of course, be viewed also in a different reference system: the rest system of A or, alternatively, the center of mass system. In this case one probes the "wee" partons of particle B, or the "wee" partons of A *and* B, resp. In order to lead to the same invariant cross section, the distribution of the wee partons inside hadrons A and B has to be universal. Finally, it should be clear that these wee partons are not necessarily small (in the transverse direction), i.e. they are not the same as the small-size partons which are probed by a pointlike photon with virtuality Q^2 in DIS.

Given the existence of the Pomeron in elastic scattering processes, Regge theory then allows to *predict* the energy dependence of inelastic production cross sections. As an example, for sufficiently large energies the scattering amplitude (at momentum transfer $t=0$) for the process $A+B \to A'+B$ has the form

$$T_{AB\to A'B} \sim \beta_{AA'} \xi s^{\alpha(0)} \beta_B \qquad (4)$$

(where ξ is a phase factor close to $e^{i\pi/2}$), provided the parity and flavor quantum numbers of the system A' are the same as those of the incoming particle A. In this case, the process is called (single) diffractive and it can, again, be viewed as the exchange of the Pomeron between A and B. In contrast to the elastic scattering, however, A is allowed to produce the excited state A'. For the special case where the invariant mass of the system A' is large: $m_p^2 \ll M_X^2 \ll s$ (triple Regge limit) the cross section for the semiinclusive process $A+B \to M_X + B$ is given by:

$$\frac{d^2\sigma}{dtdM^2} = \frac{1}{16\pi M^2}\beta_A(0)(M^2)^{\alpha(0)-1} r_{PPP}(t)(\frac{s}{M^2})^{2\alpha(t)-2}\beta_B^2(t) \qquad (5)$$

The parameters are the same as in the elastic scattering process. The only new parameter is the triple Pomeron vertex $r_{PPP}(t)$ which also has to be taken from the experiment.

The existence of diffractive scattering processes, at the same time, illustrates one of the fundamental problems of strong interactions at high energies. Clearly the square of the amplitude (4) provides, via the optical theorem, a contribution to the total cross section (1):

$$\sigma_{tot}(AB) \sim \frac{1}{s^2}\sum_X |T_{AB\to X}|^2. \qquad (6)$$

However, inserting (4) (or eq.(5)) on the rhs of (6) and making use of the Pomeron intercept in (1), the energy dependence on the rhs exceeds that on the lhs: at very large energies, the energy dependence of (1), (4), and (5) therefore, will have to be modified. In other words, the energy exponents in (1), (4), and (5) can be correct only for an intermediate energy range, and they cannot represent predictions of a truely unitary high energy theory of strong interactions. In the past this observation has been the starting point for the development of highly sophisticated formalisms, e.g. critical reggeon field theory [7, 8] which successfully avoids the inconsistency mentioned before but will apply, at best, only at ultrahigh energies. An attempt of deriving this reggeon field theory from

QCD has been outlined in [9].

2. The Hard Pomeron

Turning now to the deep inelastic structure function F_2, the connection with the total cross section of the elastic scattering process γ^*+proton is given by:

$$\sigma_{tot}(\gamma^* p) = \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2). \quad (7)$$

Beginning with photoproduction at $Q^2 = 0$, the energy dependence of the total cross section has been found to be completely consistent with the soft Pomeron [10] For $Q^2 \neq 0$ it has been observed [11] that F_2 rises, and this rise can be described by a power law $\sim (1/x)^\lambda$, with $\lambda \approx 0.2...0.4$. This rise is observed at Q^2 values down to $Q^2 = 2GeV^2$. A simple extrapolation of the "old" Pomeron from photoproduction at $Q^2 = 0$ up to the deep inelastic region fails [12] to describe this rise. Using the same notation as in elastic hadron scattering, this rising cross section has been been named the "hard Pomeron", in contrast to the "soft" Pomeron which would have predicted $F_2 \sim (1/x)^{\alpha(0)-1=0.08}$. The discovery of this "new" Pomeron, in my opinion, is one of the most important HERA results obtained so far.

Since deep inelastic scattering (at large Q^2 and not too small x) allows the use of perturbative QCD, it is natural to ask for an explanation of this rise. Presently there exist two approaches of adressing this question: either the hard Pomeron is interpreted as a manifestation of the BFKL Pomeron [13], or, more conventional, as the small-x tail of the usual DGLAP [14] evolution.

Let me begin with the first alternative. The BFKL Pomeron represents the leading logarithmic approximation for the elastic scattering of virtual gluons in the Regge limit. It predicts:

$$\begin{aligned} T(s,0) &\sim const \cdot s^{1+\omega_{BFKL}} \\ \omega_{BFKL} &= \frac{4N_c \ln 2\alpha_s}{\pi} \approx 0.5 \end{aligned} \quad (8)$$

When applying this approximation to deep inelastic scattering, one expects for the asymptotic behavior in $1/x$:

$$F_2(x, Q^2) \sim x^{-\omega_{BFKL}}. \quad (9)$$

In a realistic analysis there are corrections to this leading term, which lead to an effective power smaller than ω_{BFKL}. To make a real "BFKL prediction" for the gluon structure function at small x is very difficult: the treatment of the infrared region inside the BFKL evolution provides some systematic uncertainty. Fits to the data, on the other hand, are compatible with a power behavior where the exponent lies in the range 0.2 - 0.4 (e.g. 0.32 at $Q^2 = 20GeV^2$ [16]). One therefore concludes that the observed rise is compatible with the BFKL prediction. Of course, this is not in any conflict with the standard DGLAP evolution: the BFKL Pomeron provides the x-shape at some input scale Q_0^2, and DGLAP describes the evolution in Q^2. A recent analysis [16] compares data with both the conventional DGLAP evolution and the BFKL evolution, and one again reaches the conclusion that the data are compatible with the BFKL Pomeron.

In this interpretation of the hard Pomeron the physical picture of the deep inelastic scattering process is easily compared to what has been said befoere about the soft Pomeron: in the proton rest system the photon creates the $q\bar{q}$ pair long before it reaches the proton. This small size (in the transverse direction) color dipole system [15] then radiates a gluon with a smaller momentum fraction which subsequently emits another gluon with an even smaller momentum fraction. This sequence of decays continues until the longitudinal momenta are small enough, and the gluons ("wee partons") interact with the proton at rest. Along this chain of decays (ladders) the longitudinal momentum fractions of the produced gluons are strongly ordered, i.e. they become smaller and smaller. For the transverse momenta, on the other hand, such an ordering does not exist: initially the system has a small transverse size (k_t^2 is of the order Q^2), but then the variable $\ln k_t^2$ follows a random walk, and with a nonzero probability it can be smaller or bigger than in the previous step. If one analyzes the same amplitude in another reference system, e.g. in the Breit system where the photon is slow, the picture is quite different. Now the chain of decays starts in the fast proton, long before it reaches the photon. The wee partons which appear at the end of this deay chain are coming from the proton, whereas in the previous case they appeared to be offsprings of the photon fluctuation.

Summarizing this explanation of the hard Pomeron, the BFKL scenario is compatible with the data, but it is not compelling. From the theoretical viewpoint, it seems very unsatisfactory that we do not yet know sufficiently well (see below) the corrections to the BFKL Pomeron. As a result, we cannot really estimate where the BFKL approximation is applicable. Nevertheless, theorists believe that the BFKL Pomeron provides the most promising starting point for entering the low Q^2/low x region: that is why it seems so important to establish its existence in F_2.

An alternative interpretation of the observed rise of F_2 can be obtained within the usual DGLAP framework, if one allows the evolution to start at a sufficiently low Q_0^2 scale. As it has been shown many years ago [17], the small-x behaviour of the gluon structure function is of the form:

$$xg(s,Q^2) = const \cdot \left(\frac{\ln t/t_0}{\ln 1/x}\right)^{\frac{3}{4}} \exp\left(\sqrt{\frac{48}{\beta_0}\ln(t/t_0)\ln(1/x)}\right) \quad (10)$$

where $t = \ln Q^2/\Lambda^2$, $t_0 = \ln Q_0^2/\Lambda^2$. This formula also describes a rise at small x. A similar form (with a slightly modified prefactor) holds for F_2. Numerical studies have shown that a valence type input (i.e. $q(x,Q^2)$ and $xg(x,Q^2)$ vanish at small x) at the scale $Q_0^2 = 0.36GeV^2$ [18] or a flat input (i.e. $xg(x,Q^2)$ becomes constant as $x \to 0$) at $Q_0^2 = 1GeV^2$ [19] † can account for the observed rise at HERA. Additional evidence for this interpretation comes from the double asymptotic scaling analysis [20]: eq.(2) suggests that, rather than $\ln 1/x$ and $t = \ln Q^2/\Lambda^2$ a more natural choice of variables is

$$\sigma = \sqrt{\ln(t/t_0)\ln(x_0/x)}, \qquad \rho = \sqrt{\ln(t/t_0)/\ln(x_0/x)}. \quad (11)$$

For example, dividing the observed F_2 by the factors exhibited in (10), the remainder becomes constant at large ρ (this requires $Q_0^2 = 0.5GeV^2$) [21]. This indicates that the data are close to the functional form (10).

There is, however, some warning coming from an analysis of higher order terms in the anomalous dimensions [22, 23, 24]. DGLAP evolution is usually performed in the NLO approximation. The estimates performed in [22, 23] show that in the small-x region this approximation is not very accurate, in particular if the Q^2 evolution starts from a flat input: in this case the result of the DGLAP evolution changes if, e.g. in the anomalous dimension γ_{gg} of the two gluon operator, singular higher order terms of the form $(\frac{\alpha_s}{\omega})^n$ are taken into account. So far, our knowledge of these terms is rather limited. In the matrix of the color singlet channel, we know the leading terms for γ_{gg} [25] and γ_{gq} [26]

$$\gamma_{gg} = \sum_n (\frac{\alpha_s}{\omega})^n a_n$$
$$\gamma_{gq} = \sum_n (\frac{\alpha_s}{\omega})^n b_n \quad (12)$$

and the leading terms for γ_{qq} and γ_{qg} [26]:

$$\gamma_{qq} = \alpha_s \sum_n (\frac{\alpha_s}{\omega})^n c_n$$
$$\gamma_{qg} = \alpha_s \sum_n (\frac{\alpha_s}{\omega})^n d_n. \quad (13)$$

For a consistent analysis we clearly need the higher order corrections for γ_{gg} and γ_{gq} of the form $\alpha_s \sum (\frac{\alpha_s}{\omega})^n a'_n$. Also, including these singular terms into the DGLAP evolution one is violating the momentum conservation during the DGLAP evolution. Despite all these uncertainties, the analysis clearly demonstrates the numerical importance of the resummation, and it signals that we may be close to the limit of applicability of the DGLAP framework.

Given the fact that two explanations of the hard Pomeron are competing with each other, one clearly has to search for further ways of discriminating between the two. One method is the measurement of the transverse energy in the central region. If, at a given Q^2, the x-shape is in accordance with the BFKL approximation, one expects to see in the final state traces of the BFKL dynamics, in particular the distribution in transverse momentum [27] which, because of the absence of ordering in k_t^2, is spread out both towards large and small momenta. Compared to the other scenario, where the final state is generated through the standard QCD evolution and its strong ordering in transverse momentum, the BFKL- type final state is therefore expected to have larger transverse energy

† Recently, low-Q^2 data from the shifted vertex indicate that the rise of F_2 is present even at $Q^2 = 1.5GeV^2$: in this case the flat input has to move to a somewhat lower scale $Q_0^2 < 1GeV^2$.

than the DGLAP final state. Morover, the average transverse energy is expected to grow with $1/x_B$, whereas the DGLAP picture is predicted to show the opposite trend. Both these "BFKL footprints" are seen in the data [28], but the close comparison of the data with the "theoretical predictions" of BFKL and DGLAP faces difficulties: existing analytical calculations do not include hadronization effects, which may be substantial. The actual comparison is done with two different Monte Carlo calculations which are neither pure BFKL nor pure DGLAP. Further improvement of this analysis is clearly needed.

As far as the "existence" of the BFKL Pomeron is concerned, deep inelastic scattering at HERA offers the possibility of a very clean test [29]: the measurement of inclusive jets in the forward direction with longitudinal momenta as close possible to the proton and transverse momenta of the order of the photon mass $\sqrt{Q^2}$. For the production of gluons between the forward jet and the current jet DGLAP is not applicable since the momentum scales of both jets are similar: so there is no ambiguity between BFKL and DGLAP. The signal for the presence of the BFKL Pomeron is a strong rise of the cross section in $1/x_B$, and such a rise is observed in the data [28]. A recent study [30] presents a more detailed comparison of the data with BfKL and fixed order matrix element calculations, and the evidence for the BFKL Pomeron is encouraging.

After this discussion it seems clear that the explanation of the hard Pomeron and its connection the soft Pomeron is one of the most important theoretical issues. What we seem to have learned is that by changing the momentum scale of the scattering object at the one end of the exchanged Pomeron - e.g. the mass Q^2 of the heavy photon which fluctuates into a $q\bar{q}$-pair - we see different shapes in $W^2/Q^2 = 1/x$, i.e. different dependence upon the energy of the scattering process. If we start from the large Q^2 region, where the expansion in twist holds, and try to move to smaller Q^2, we are facing the question of higher twist: at what value of Q^2, x does it become relevant, what can be said about its magnitude of? For the small-x region, we have some knowledge about higher twist: generalized evolution equations have been formulated in [31]. The singular part of the four gluon operator which is expected to be dominant in the small-x region is known [32, 33]. However, so far no attempt has been made to perform a numerical study with these tools. I think it is now important to adress this question seriously. In the language of the BFKL Pomeron, the connection between deep inelastic scattering at small x and the soft Pomeron in photoproduction is related to the unitarization of the BFKL Pomeron. This issue will be discussed in the final part of this article.

3. Diffractive Dissociation

The observation of a rather large (about 10 % of all DIS events) number of events with a rapidity gap between the outgoing proton and the diffractive excitation of the photon provides completely new insight into the Pomeron, both the hard and the soft one. Summarizing theoretical expectations, we expect that the Pomeron across the rapidity gap can be either hard or soft, depending upon the diffractive final state of the photon. If one sums over all states with invariant mass M, i.e. one measures the inclusive cross section, it is, a priori, not clear which Pomeron will dominate. On the theoretical side, there seems to be a slight preference for the soft Pomeron to dominate. However, quantitative statements are difficult to make, and therefore the answer from the experiment is particularly interesting and important. As to the theoretical side, let me first try to illustrate the ideas and the physical picture; the second part of this section will then be more quantitative.

The process of DIS diffractive dissociation is most conveniently discussed in the proton rest system: at small x, the photon fluctuates into the quark-antiquark system, and the lifetime ot this fluctuation is of the order $1/2M_p x$. The hardness of the photon translates into a small transverse (w.r.t. the photon direction) size of the $q\bar{q}$-pair. Let us begin with the simplified case where the final state of the photon consists just of this $q\bar{q}$-pair (i.e. no extra gluons) which scatters elastically off the proton. The dynamics of this process now depends crucially upon the kinematic configuration of the $q\bar{q}$-pair. If the transverse momenta are small and the mass M is of the order $\sqrt{Q^2}$, the longitudinal momenta should be rather asymmetric: one of the quark or the antiquark carries almost all the longitudinal momentum of the photon, whereas the momentum fraction of the other one is small. In the $\gamma^* - p$ center of mass system, the produced quark and antiquark are almost collinear with the proton direction ("aligned jet model" [34]). The elastic scattering of a quark with small virtuality off the proton proceeds via the exchange of a (soft) Pomeron: this configuration should therefore come with the characteristic energy dependence of the soft Pomeron.

In addition there is, however, also the configuration where the momentum scale of the quark and the antiquark is not so small, and the elastic scattering of the $q\bar{q}$ pair off the proton proceeds via the hard Pomeron (e.g. the BFKL Pomeron): the final $q\bar{q}$ state should have larger transverse momenta, and the energy dependence will be steeper.

To be more realistic, one has to allow also for the production of gluons. In particular for the first case (small transverse momenta), we have to keep in mind that in QCD the creation of a quark with small transverse momentum from a hard photon is accompanied by gluon radiation: we therefore expect that one of the fermions inside the $q\bar{q}$ will emit a few gluons (and thereby diminuish its initial hardness) before it scatters off the proton. In addition, there is the process where the elastic scattering occurs between a gluon and the proton: this gluon will be emitted from the quark or the antiquark, and before it becomes sufficiently soft it will also radiate gluons (or additional $q\bar{q}$ pairs). Translating these processes into the reference frame where the proton is fast, we arrive at the Ingelman-Schlein [35] picture of the Pomeron structure function: the Q^2 evolution of the partons inside the Pomeron starts at a low momentum scale Q_0^2 and then proceeds via the DGLAP evolution equations. In the first type of process the evolution starts with a quark inside the Pomeron, in the second with a gluon. Note that Q_0^2 has to be above the scale of the quark or gluon which, in the previous discussion, was the parton that performed the elastic scattering with the proton.

Additional gluons have to be included also in the "hard" configuration of the $q\bar{q}$-pair: after their emission from the initially produced $q\bar{q}$ pair, the hard Pomeron (consisting of of a two gluon system) will interact with the complete $q\bar{q} - n\, gluon$ system. There are theoretical reasons to expect that the Q^2 evolution of this case may be different from the previous (soft) case.

Most important is the question which configuration will dominate: the one where the exchanged Pomeron is hard, or the soft case. Returning to the simple $q\bar{q}$ final state, one expects that small transverse momenta (i.e. a large size in the transverse direction) lead to a bigger cross section than small sizes, and hence the soft Pomeron should dominate. On the other hand, the steeper increase in $1/x$ of the hard Pomeron leads, at small x, to an increase of the hard contribution in the final state. Which of these competing mechanisms wins can be decided only within specific models to which I will return below.

Discussion of the data requires a few comments on the notation. With the variables

$$x_P = \frac{Q^2 + M^2 - t}{Q^2 + W^2}, \quad \beta = x/x_P = \frac{Q^2}{Q^2 + M^2 - t} \tag{14}$$

the differential cross section reads:

$$\begin{aligned} \frac{d^4\sigma^D}{dx dQ^2 dx_P dt} &= \frac{4\pi\alpha^2}{xQ^2} \\ &\quad \left[(1 - y + \frac{y^2}{2})\frac{d^2F_2^D}{dx_P dt} - \frac{y^2}{2}\frac{d^2F_L}{dx dt}\right] \\ &\approx \frac{4\pi\alpha^2}{xQ^2}(1 - y + \frac{y^2}{2})\frac{d^2F_2^D}{dx_P dt} \end{aligned} \tag{15}$$

(the upper index "D" indicates that, in contrast to the totally inclusive cross section, the final states are restricted to be diffractive, i.e. to contain the rapridity gap between the proton and the excitation of the photon. In the second line, F_L is assumed to be small compared with F_2 [36]). In the region of large M^2 (i.e. small β) the use of eq.(5) suggests the following ansatz (note that $W^2 \gg Q^2$):

$$\begin{aligned} \frac{d^2F_2^D}{dt dx_P} &= W^2 \frac{d^2F_2^D}{dt dM^2} \\ &= \beta_\gamma(0)(\frac{M^2 + Q^2}{Q^2})^{\alpha(0)-1} r_{PPP}(t) \\ &\quad (\frac{W^2}{Q^2 + M^2})^{2\alpha(t)-1}\frac{\beta_P^2(t)}{16\pi} \\ &= F_2^P(\beta, Q^2, t)(\frac{1}{x_P})^{2\alpha(t)-1}\frac{\beta_P^2(t)}{16\pi}. \end{aligned} \tag{16}$$

This equation defines the "Pomeron structure function" F_2^P: the crucial assumption, motivated by Regge theory [37], is that its dependence upon x and x_P is only through β (eq.(11)). After averaging over t it is this form of the cross section that has been used to analyze the data. ¿From what has been said before it follows that the exchange of the soft Pomeron results in the power $2\alpha(0) - 1 \approx 1.17$ for the x_P dependence, whereas the hard Pomeron leads to a bigger number: $2\alpha(0) - 1 > 1.4$ (if one uses the power 0.2 for the hard Pomeron at Q^2 around $10 GeV^2$) or even ≈ 2.0 for the BFKL Pomeron.

Published values for the exponent $2\alpha(t) - 1$ (averaged over t) are [38, 39, 40]:

$$\begin{array}{lll} 1.19 & \pm 0.06 & \pm 0.07 \\ 1.30 & \pm 0.08 & ^{+0.08}_{-0.14} \\ 1.47 & \pm 0.03 & ^{+0.14}_{-0.10}\,. \end{array} \qquad (17)$$

The third value [40] is based upon a new method of subtracting the nondiffractive background. In (17) the first measurement gives the impression that it is mainly the soft Pomeron which is responsible for the rapidity gap, whereas the third one favors the hard Pomeron. [38, 39] also present evidence for the factorization in (16): within the errors, the power of $1/x_P$ does not vary with Q^2 or β.

What are the potential implications of these measurements? If it is the soft, hadronic Pomeron which produces the rapidity gap, then we are answering the question originally raised by Ingelman and Schlein, i.e. we are measurung the partonic structure of the Pomeron seen in hadron hadron scattering. Following the idea of treating the Pomeron in very much the same way as the proton, several groups [41, 42, 43, 44] have performed a standard QCD analysis of the Pomeron structure function. Staring from some initial conditions for quarks and gluons inside the Pomeron, DGLAP evolution equations are used to study the Q^2-evolution. Particular emphasis has been given to the question whether the Pomeron has a strong gluon component: depending upon the analysis, there is common agreement that more than 50% of the total momentum of the Pomeron is carried by gluons. Somewhat peculiar is the observation that F_2^P does not seem to fall with Q^2 even at rather large values of β: possible explanations are a pointlike component inside the Pomeron [43] or a strong peaking in the gluon distribution near $\beta = 1$.

On the other hand, if it is the hard Pomeron which dominates the rapidity gap events, we have a new way of testing our understanding of the hard Pomeron. For example, what we have learned from F_2 is that the hard Pomeron appears in the elastic scattering of a small-size system (e.g. a $q\bar{q}$ fluctuation of a heavy photon) on the proton. Consequently, one would expect to find some "hardness" in the diffractive final state of the photon, e.g. a strong contribution of larger transverse momenta. To make these theoretical expectations more precise, one has to perform an analysis of diffractive dissociation which is based upon perturbative QCD, in particular on the BFKL Pomeron as a model for the hard Pomeron. After earlier QCD studies of the production of jets with large transverse momenta [45, 46, 47], more recently a BFKL-type analysis of the inclusive cross section has been performed [48, 50]; compared to the earlier studies this analysis has the advantage of including also contributions with smaller transverse momenta. Interesting enough, a careful analysis of the rather sophisticated analytic expressions for the cross section leads to the conclusion [49] that the BFKL Pomeron gets its main contribution from the region of small intrinsic transverse momenta where the corrections to the BFKL Pomeron are expected to be large and turn the hard Pomeron into the soft one! Consequently, the final state will not be dominated by large transverse momenta, and the energy dependence should be close to the soft Pomeron. So, from this theoretical study, it seems as if the hard Pomeron does not want to play the dominant role in the diffractive dissociation, and further clarification is clearly needed.

Recently alternative interpretations of the diffractive cross section have been suggested which do not relate to the soft or the hard Pomeron at all [51]. In this picture, the interaction between the produced $q\bar{q}$-pair and the proton at rest proceeds via the exchange of a single hard gluon. The probability of finding such a gluon inside the proton follows from the gluon structure function. After this single gluon exchange the quark antiquark system would be in a color octet state; this color is neutralized ("randomized") by further interaction of the quarks with the background field of the proton. Straightforward predictions of this model are the ratio of diffractive events and total DIS events and the approximate independence of x_P of F_2^D/F_2. Ideas very close to this picture have been developed also in [52], and they have been used to develop a new Monte Carlo which seems to describe the rapidity gap events rather well.

So far all the discussion has been about open quark and gluon production, i.e. no further constraint has been imposed on the diffractive final state. As a very interesting example of a *specific* final state I would like to mention the diffractive production of vector mesons. For the J/Ψ production (both photoproduction and electroproduction) [53] and for DIS ρ, ϕ-production from longitudinal photons [54] it has been shown that the cross section is calculable in perturbative QCD, and, at $t = 0$, is proportional to the square of $xg(x, Q^2)$. Data [55, 56] show, in fact, that the cross sections rise faster than predictd by the soft Pomeron [57]. The presence of the hard Pomeron is explained by the large scale set by the photon mass or the mass of the charm quark, which fits into what we have learned about the hard Pomeron from F_2.

4. The Future: Hope for Unification

In this final part of the talk let me return to the transition from the hard to the soft Pomeron, i.e. from the (partly perturbative) total cross section at large Q^2 to the (nonperturbative) photoproduction total cross section at $Q^2 = 0$. One might hope that this transition will not be too abrupt, i.e. before nonperturbative physics sets in one will be able to see the first corrections to the leading logarithmic approximation (BFKL or DGLAP). The first question, therefore, has to adress calculation of the higher order perturbative corrections. I will limit myself to the case of the BFKL Pomeron.

Generally speaking, one may think of two different strategies for calculating corrections to the BFKL Pomeron and, finally, approaching the full QCD theory in the Regge limit. First, one may stay in the framework of ladder diagrams and search for corrections to the BFKL-kernel and the gluon trajectory function. They are of the order $O(\alpha_s^2)$, and in the scattering amplitude they are down by one power of $\ln 1/x$ compared with the leading logarithmic aproximation. This involves diagrams which belong to vertex corrections, self energies, and the production of two-gluon states with a small rapidity gap. At this stage also fermions will come in: the fermion box diagrams which are known from the tower diagrams in QED [58, 59]. One consequence of all these contribution will be that they provide the first logarithmic correction to the fixed coupling constant. One also expects that the power of s (or $1/x$) which governs the high energy behaviour will receive corrections of the order α_s^2. This line of calculations is being persued by Fadin and Lipatov, and recent results have been published in [60]. Other attempts in this direction start from t-channel unitarity arguments [61] or an effective action [62]. Another important benefit from calulating this type of non-leading contributions is the possibility of obtaining higher order contributions to the gluon anomalous dimension. In analogy to [25] where the eigenvalues of the BFKL kernel have been used to calculate all terms of the form $(\frac{\alpha_s}{n-1})^k$ in the gluon anomalous dimension, one expects to obtain, from [60], the contributions of the form $\alpha_s(\frac{\alpha_s}{n-1})^k$. As discussed in section 3, these terms are numerically important in the GLAP evolution, in particular if the input distribution is flat in $1/x_B$.

It is, however, clear that these corrections to the BFKL-kernel are not enough. In particular, they will not help to cure the violation of unitarity which manifests itself in the power of s (eq.(8)). The restauration of unitarity requires contributions which go beyond the one-ladder structure: diagrams with more than two (reggeized) gluons in the t-channel. A first generalization of the BFKL equation in this direction has been suggested in [64]. A complete analysis of the four gluon case which includes the calculation of the $2 \rightarrow 4$ gluon transition vertex is given in [32, 48]. Presently, the most attractive long term program consists of the derivation and solution of an effective 2+1 dimensional field theory. In a high energy scattering process with zero or small momentum transfer the two transverse degrees of freedom (two-dimensional impact parameter or its conjugate, the transverse momentum) and the longitudinal degree of freedom (rapidity or angular momentum of the cross channel) play completely different roles. Therefore it appears to be an attractive idea to formulate an effective field theory which lives in the two-dimensional transverse space (with rapidity as the time variable). Several attempts in this direction have already been made before [63]. But as it has been said before, the low-x limit of DIS provides a new direction of attacking the Regge limit.

Starting point for the formulation of such a field theory are the (perturbative) Green's functions $G_{n\rightarrow m}(\rho_1, ..., \rho_n; \rho_1', .., \rho_m')$ which describe the transition: n reggeized t-channel gluons $\rightarrow$ m reggeized t-channel gluons. They live in the two-dimensional impact parameter space and depend upon angular momentum ω which plays the role of energy. The simplest example for such a Green's function is $G_{2\rightarrow 2}$, the BFKL-Pomeron. The first nontrivial generalization to this is the function $G_{2\rightarrow 4}$ which has been derived in [65, 48] and contains, as a new kernel, a 2 $\rightarrow$ 4 gluon transition vertex. For the BFKL kernel we know from [67] that it is invariant under Moebius transformations; for the number changing 2 $\rightarrow$ vertex the invariance has been proven recently [66]. We therefore expect that these Green's functions can be used to define a conformal invariant field theory:

$$G_{n\rightarrow m}(\rho_1, ..., \rho_n; \rho_1', ..., \rho_m') \sim < \phi(\rho_1)...\phi(\rho_n)\phi(\rho_1')...\phi(\rho_m') > \qquad (18)$$

(note that these fields cannot be identified with the QCD-gluon field operators; the property of being "reggeized" makes the gluons already somewhat "composite").

As to specific properties of this field theory, so far only a special approximation has been investigated [68]: ignoring the number changing vertex, one reduces the field theory to the quantum mechanics of n pairwise interacting particles. Taking the limit of large N_c and making use of the holomorphic factorization of the BFKL kernel, further simplification is achieved: the problem becomes one dimensional. For this problem it has been shown [68, 69] that it can be reduced to the s=0 XXX Heisenberg model with the symmetry group SL(2,C) and that it is soluble. Formula have been given for calculating the energy spectrum, but so far only the case n=2 has been computed exactly. The general case is under study [70, 71, 72]. In a future step also the higher order corrections to the BFKL kernel and the gluon trajectory function which have been mentioned at the beginning of this section have to be included: recently an alternative field theoretic formulation (effective action) has been suggested [73] which takes into account these corrections to all orders.

5. Conclusions

No doubt that HERA measurements have provided new insight into the old Pomeron problem - in particular the steeper energy dependence of the "hard Pomeron" and the subtle mixture of the "hard" and the "soft" Pomeron in the diffractive dissociation. Furthermore, the advent of "Low-x Physics" has generally stimulated new theoretical activities of studying QCD in the Regge limit. All this represents a remarkable progress in understanding strong interactions at high energies.

References

[1] A.Donnachie, P.V.Landshoff, *Phys.Lett.* **B 296** (1992) 227.

[2] Earlier Regge pole fits to proton proton scattering with similar numbers are published in; P.D.B.Collins, F.D.Gault, and A.D.Martin, *Nucl.Phys.***B80** (1974) 135.

[3] H.Cheng, J.K.Walker, and T.T.Wu, *Phys.Lett.***B 44** (1973) 97.

[4] C.Bourrely, J.Soffer, and T.T.Wu, *Phys.Lett.* **B 339** (1994) 322.

[5] V.N.Gribov, Proceedings of the 8th Leningrad Winter School, 1973, p.1.

[6] R.P.Feynman, Photon Hadron Interactions, Frontiers in Physics, W.A.Benjamin, Inc., 1972.

[7] H.D.I.Abarbanel, J.B.Bronzan, R.L.Sugar, A.R.White, *Phys.Rep.* **21** C (1975) 119.

[8] M.Moshe *Phys.Rep.* **37** C (1978) 255.

[9] A.R.White, *Int.J.Mod.Phys.***A8** (1993) 4755; *Phys.Rev.***D29** (1984) 1435.

[10] ZEUS Collab. M.Derrick at al., *Zeitschr.Phys.* **C63** (1994) 391;
H1 Collaboration, DESY-95-162.

[11] J.Dainton, these Proceedings.

[12] A.Donnachie and P.V.Landshoff, *Zeitschr.Phys.* **C 61** (1994) 139; H1 Collaboration, *Nucl.Phys.***B 407** (1993) 515; H1 Collaboration, contribution to the EPS conference in Bruxelles, 1995.

[13] E.A.Kuraev, L.N.Lipatov, V.S.Fadin, *Sov.Phys.JETP* **45** (1977) 199; Ia.Ia.Balitski, L.N.Lipatov, *Sov.J.Nucl.Phys.* **28** (1978) 822.

[14] V.N.Gribov and L.N.Lipatov, *Sov. J.Nucl.Phys.* **15** (1972) 438 and 675;
G.Altarelli und G.Parisi, *Nucl.Phys.* **B126** (1977) 298;
Yu.L.Dokshitzer, *Sov.Phys.JETP* **46** (1977) 641.

[15] A.H.Mueller, *Nucl.Phys.*B 415 (1994) 373; A.H.Mueller and B.Patel, *Nucl.Phys.***B 425** (1994) 471; A.H.Mueller, *Nucl.Phys.***B 437** (1995) 107; Zhang Chen and A.H.Mueller, *Nucl.Phys.***451** (1995) 579. A.Bialas and R.Peschanski, *Phys.Lett.*B 355 (1995) 301; R.Peschanski, these Proceedings.

[16] power of F2

[17] A.De Rujula, S.L.Glashow, H.D.Politzer, S.B.Treiman, F.Wilczek, and A.Zee, *Phys.Rev.* **D10** (1974) 1649.

[18] A.Vogt, these proceedings.

[19] R.D.Ball and S.Forte, CERN-TH 7265/94.

[20] R.D.Ball and S.Forte, *Phys.Lett.***B 335** (1994) 77 and *Phys.Lett.* **B 336** (1994) 77; J.R.Forshaw and R.G.Roberts, *Phys.Lett.* **B 351** (1995) 308.

[21] H1 Collab., DESY-95-081.

[22] K.Ellis, Z.Kunszt, E.Levin, *Nucl.Phys.***B 420** (1994) 517; ERRATUM-ibid.**B433** (1995) 498.

[23] R.K.Ellis, F.Hautman, and B.R.Webber, *Phys.Lett.* **B 348** (1995) 582.

[24] R.D.Ball and S.Forte, *Phys.Lett.***B 351** (1995) 313.

[25] T.Jaroscevicz, *Phys.Let.*B **116** (1982) 291.

[26] S.Catani and F.Hautman, *Phys.Lett.* **315** (1993) 157 and *Nucl.Phys.* **B 427** (1994) 475.

[27] J.Kwiecinski, A.D.Martin, P.J.Sutton, and K.Golec-Biernat, *Phys.Rev.***D50** (1994) 217; K.Golec-Biernat, J.Kwiecinski, A.D.Martin, and P.J.Sutton, *Phys.Lett.***B 335** (1994) 220.

[28] H1 Collaboration, DESY-95-108 and *Phys.Lett.* **B 356** (1995) 118.

[29] A.H.Mueller, *Nucl.Phys.B* (Proc.Suppl.) **18C** (1991) 125; J. Bartels, A.DeRoeck, M.Loewe, *Z.Phys.* **C54** (1992) 635; J.Bartels, M.Besancon, A.De Roeck, J.Kurzhoefer, in *Proceedings of the HERA Workshop 1992* (eds.W.Buchmüller and G.Ingelman), p.203; J.Kwiecinski, A.D.Martin, P.J.Sutton, *Phys.Lett.* **B 287** (1992) 254; *Phys.Rev.* **D 46** (1992) 921; W.-K.Tang, *Phys.Lett.* **B 278** (1991) 363.

[30] J.Bartels, V.DelDuca, A.DeRoeck, D.Graudenz, M.Wuesthoff, DESY preprint in preparation.

[31] A.P.Bukhvostov, G.V.Frolov, L.N.Lipatov, E.A.Kuraev, *Nucl.Phys.***B258** (1985) 601.

[32] J.Bartels, *Phys. Lett.* **B 298**(1993) 204.

[33] E.M.Levin, M.G.Ryskin and A.G.Shuvaev, *Nucl. Phys.***B 387** (1992) 589.

[34] V.N.Gribov, B.L.Ioffe and I.Ya.Pomeranchuk, *Yad.Fiz.***2** (1965) 768; B.L.Ioffe, *Phys.Lett.***30** (1968) 123; C.Llewllyn-Smith, *Phys.Rev.*bf D4 (1971) 2392; V.N.Gribov, *Sov.Phys.JETP***30** (1969) 709 and *ITEP School on Elementary Particles* (1973) Vol.I, p.53; J.D.Bjorken in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, p.281 (Cornell 1971); L.Frankfurt and M.Strikman, *Phys.Rep.* **160** (1988) 235.

[35] G.Ingelman und P.Schlein, *Phys.Lett* **B152** (1985) 256.

[36] G.Ingelman and K.Prytz, *Zeitschr.Phys.***C58** (1993) 285.

[37] E.L.Berger, J.C.C.Collins, E.Soper, G.Sterman, *Nucl.Phys.***B286** (1987) 704.

[38] H1 Collab., *Phys.Lett.* **B 348** (1995) 681.

[39] ZEUS Collab., DESY-95-093.

[40] ZEUS Collab., Contribution submitted to the 17th International Symposium on Lepton - Photon Interactions, Bejing, China, August 1995.

[41] T.Gehrmann, W.J.Stirling, preprint DTP/95/26.

[42] K.Golec-Biernat and J.Kwiecinski, *Phys.Lett.* **B 353** (1995) 329.

[43] B.A.Kniehl, G.Kramer, and H.G.Kohrs, *Zeitschr.Phys.***C 65** (1995) 657.

[44] A.Capella, A.Kaidalov, C.Merino, J.Tran Thanh Van, preprint LPTHE Orsay 95-33; *Phys.Lett.***B 343** (1995) 403.

[45] M.G.Ryskin, *Sov.J.Nucl.Phys.* **52** (1990) 529.

[46] N.Nikolaev, B.G.Zakharov, *Zeitschr.Phys.***C53** (1992) 331.

[47] E.Levin, M.Wuesthoff, *Phys.Rev.* **D50** (1994) 4306.

[48] J.Bartels, M.Wuesthoff, *Zeitschr.Phys.***C 66** (1995) 157.

[49] J.Bartels, H.Lotter, and M.Wuesthoff, *Zeitschr.Phys.* **C 68** (1995) 121.

[50] M.Wuesthoff, Doctoral Thesis, Hamburg 1995 and DESY-95-166.

[51] J.Ellis and H.Kowalski (unpublished); W.Buchmueller and A.Hebecker, *Phys.Lett.***B355** (1995) 537; A.R.White, ANL-HEP-PR-95-57.

[52] A.Edin, G.Ingelman, J.Rathsman, prepint TSL/ISV-95-0125, DESY-95-163.

[53] M.G.Ryskin, *Zeitschr.Phys.* **C 57** (1993) 89.

[54] S.J.Brodsky, L.Frankfurt, J.F.Gunion, A.H.Mueller, M.Strikman, *Phys.Rev.* **D 50** (1994) 3134.

[55] A.Whitfield, these Proceedings; H1 Collaboration, DESY-94-153 and *Phys.Lett.* **338** (1994) 507.

[56] A.Whitfield, these Proceedings, and ZEUS Collaboration, DESY-95-133 and *Phys.Lett.* **B 356** (1995) 601; DESY-95-052 and *Phys.Lett.***B 350** (1995) 120.

[57] A.Donnachie and P.V.Landshoff, *Phys.Lett.* B 348 (1995) 213.

[58] V.N.Gribov, C.V.Frolov, L.N.Lipatov, *Phys.Lett.***B 31** (1970) 34;
*Sov.Journ.Nucl.Phys.***12** (1970) 994.

[59] H.Cheng and T.T.Wu, *Phys.Rev.***D1** (1970) 2775.

[60] V.S.Fadin, R.Fiore, A.Quartarolo, preprint BUDKERINP-95-49, *Phys.Rev.* **D50** (1994) 5893, *Phys.Rev.* **D50** (1994) 2265,
V.S.Fadin, L.N.Lipatov *Nucl.Phys.* **B406** (1993) 259,
V.S.Fadin, R.Fiore, *Phys.Lett.* **B294** (1992) 286,
V.S.Fadin, L.N.Lipatov *JETP Lett.* **49** (1989) 352, *Sov.J.Nucl.Phys.* **50** (1989) 712.

[61] C.Coriano, A.R.White, *Phys.Rev.Lett.***74** (1995) 4980; *Nucl.Phys.***B 451** (1975) 231.

[62] R.Kirschner, Leipzig-18-1995, hep-ph/9505421.

[63] W.A.Bardeen, R.B.Pearson, E.Rabinovici, *Phys.Rev.* **D 21** (1980) 1037; L.N.Lipatov, *Zh.Eksp.Teor.Fiz.***90** (1986) 1536; H.Verlinde and E.Verlinde, Princeton preprint 1993, PUPT-1319; I.Ya.Arefeva, *Phys.Lett.***B 325** (1994) 171.

[64] J.Bartels, *Nucl.Phys.* **B175** (1980) 365; J.Kwiecinski und M.Praszalowicz, *Phys.Lett.* **B94** (1980) 413.

[65] J.Bartels, *Zeitschr.Phys.***C60** (1993) 471.

[66] J.Bartels, L.N.Lipatov, M.Wuesthoff, DESY-95-171.

[67] L.N.Lipatov, *Zh.Eksp.Teor.Fiz.***90** (1986) 1536.

[68] L.N.Lipatov, *JETP Lett.* **59** (1994) 596.

[69] L.D.Faddeev, G.P.Korchemsky, *Phys.Lett.* **B 342** (1995) 311.

[70] G.P.Korchemsky, *Nucl.Phys.*B 443 (1995) 255.

[71] Z.Maassarani and S.Wallon, Saclay preprint, June 1995.

[72] G.P.Korchemsky, preprint ITP-SB-95-25, hep-ph/9508025.

[73] L.N.Lipatov, preprint DESY-95-029.