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Non-linear QCD effects in the pomeron parton dynamics

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The x- and Q^2-dependence of the parton structure function of the pomeron is investigated based on perturbative QCD. We demonstrate that a large gluon content and small size of the pomeron leads to strong non-linear QCD effects in the Q^2-evolution as described by the Gribov–Levin–Ryskin equation. In diffractive electron–proton scattering at HERA this phenomenon should be observable and is predicted to be of larger magnitude than the corresponding non-linear effect in the proton structure function.

Diffractive processes are assumed to proceed through the exchange of a so-called pomeron ($\mathbb{P}$). Since this involves a strong interaction, it is natural to ask whether the pomeron can be understood as an object composed of partons. If so, it may be possible to probe its parton structure through a hard scattering process as suggested in ref. [1]. The UA8 experiment at the CERN p$\bar{\text{p}}$ collider has observed [2] high-$p_\perp$ jets in diffractively excited high mass states and this hard scattering phenomenon, in what is effectively pomeron–proton collisions, cannot be understood without the assumption of a parton structure of the pomeron. Furthermore, assuming the pomeron to be a purely gluonic object described by a gluon momentum density distribution [1], the data [2] seemed to prefer a soft distribution and be in reasonable agreement with this model [1]. A similar evidence comes from diffractive production of bottom mesons as observed by UA1 [3], where again a soft gluon distribution in the pomeron was preferred.

In this letter we consider the pomeron structure inclusively, i.e., regardless of the hadronic final state, by studying its structure function in deep inelastic scattering (DIS). This is analogous to the well-known DIS measurements of the proton structure function and may be achieved, as illustrated in fig. 1a, by electron–proton scattering with the extra condition that the proton has to be scattered quasi-elastically to ensure the diffractive nature of the interaction. The exchanged pomeron will then be probed by the electron and its parton content can be measured, like in normal DIS, as a function of momentum fraction x and resolution Q^2. We expect perturbative QCD to be applicable, as for the proton structure function, and we calculate the resulting scaling violations. In particular, we consider the connection between the pomeron and QCD at small x [4]. We therefore focus on the non-linear QCD effects caused by the screening taking place with high parton densities at small x, as described by the Gribov–Levin–Ryskin (GLR) equation [5], and compare with standard Gribov–Lipatov–Altarelli–Parisi evolution [6].

The process we have in mind proceeds as illustrated in fig. 1a. A pomeron is emitted from the proton in the lower vertex with a small squared momentum transfer t and with a fraction $x_{\mathbb{P}} = 1-x_p$ of the proton momentum. This pomeron then interacts with the electron in a large momentum transfer process, described by the usual DIS variables $Q^2 = -q^2 = -(p_e - p_{e'})^2$ and (Bjorken) $x = Q^2/2P_p \cdot q$, and produces the hadronic final state X of mass M_X. This type of factorisation assumption [1,7] is based on the success of pomeron phenomenology for diffractive dissociation and elastic scattering [8]. Thus, the pomeron is treated as a quasi-hadron and we will further follow the old suggestion [9] that it is dominantly composed of gluons. This approach has been used widely [1,7,10,11], but is not free from objections [12,13].

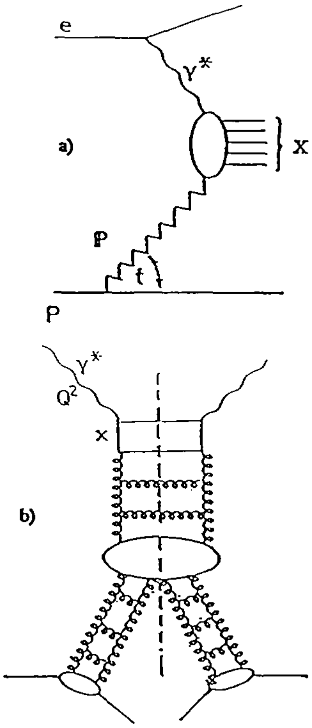

Fig. 1. Probing the pomeron structure by diffractive deep inelastic electron–proton scattering. (a) General diagram with produced hadronic system X well separated in phase space from the quasi-elastically scattered proton. (b) The squared scattering amplitude in terms of perturbative QCD ladders. The cut (dashed line) is made to illustrate the diffractive final state.

Neglecting, for simplicity, any quark component in the pomeron, its parton structure is then described by a gluon density distribution $g(z,Q^2)$, where $z = x/x_{\mathbb{P}}$ is the momentum fraction of the parton in the pomeron.

In ordinary QCD evolution of DIS structure functions (Altarelli–Parisi equations) only the splitting of partons are taken into account, i.e., the processes $q \to qg$, $g \to q\bar{q}$ and $g \to gg$. With the increasing parton density at small x, however, the inverse recombination processes should also become important and prevent the otherwise unbounded increase of the parton density functions. The gluon recombination effect is incorporated in the GLR equation [5], which is derived in perturbative QCD from more complicated Feynman diagrams where the evolution ladders form fan diagrams. Only gluons are here taken into account, since they dominate the proton structure function and its evolution at small x. This approximation should be adequate for our application to the pomeron since we have assumed it to be a purely gluonic object. In ref. [11] an approach was introduced to obtain the pomeron structure function from the GLR equation by making the identification of deep inelastic scattering on the pomeron (fig. 1a) with the fan diagram in fig. 1b.

The evolution of the gluon momentum distribution can, when quarks are neglected, then be written in the comprehensible form [14,15]

$$\frac{\partial zg(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} z \int_z^1 \frac{dy}{y^2}\, yg(y,Q^2) P_{gg}\left(\frac{z}{y}\right) - \frac{81\alpha_s^2(Q^2)}{16R^2Q^2}\theta(y_{max}-z) \int_z^{y_{max}} \frac{dy}{y}\left[yg(y,Q^2)\right]^2 . \quad (1)$$

The first term represents the normal Altarelli–Parisi splitting $g \to gg$ and is hence linear in the gluon field. The second term gives the novel non-linearity since the joining of two gluons requires a two-gluon distribution which can be approximated by the single gluon distribution squared. The negative sign of this term leads to a reduction, or screening, of the gluon density at small z. As a reflection of the higher twist nature (in the sense of parton-parton interaction) of this gluon recombination term it contains a factor $1/Q^2$, whose dimension is balanced by a free parameter R representing the size of the object.

Numerical estimates of this screening effect on the proton structure function have been made [15,16]. They are found to be rather small in the kinematical domain of HERA and it is not yet clear whether they can be observed. The reason for this smallness is threefold (cf. eq. (1)): x-values much smaller than 10^{-4} are not measurable at HERA, the gluon distribution in the proton is not large enough and the proton radius is not so small. Whereas the first two ingredients can hardly be changed, it has been speculated that a smaller effective radius could occur in the case of so-called hot spots [17,18], i.e., smaller regions within the proton where the parton density is higher than the average. This may occur in some quantum fluctuations, perhaps associated with dressed valence quarks [17] giving an effective radius around 2 GeV^{-1}, instead of the normal proton radius 5 GeV^{-1}, which would amplify the screening term correspondingly [15]. Alternatively, correlations of jets in DIS hadronic final states may be used to investigate the QCD evolution in a restricted region of the proton [18,19].

When applying eq. (1) to the pomeron it is immediatly clear that the screening term could play an important role if the pomeron has a large gluon component, as assumed here, and has the small radius that seems likely. In the approach to the pomeron used here one could naivly view the pomeron as a part of the proton and hence guess that its dimension is a fraction of the protons. Having to do with diffractive scattering one could intuitively expect that this fraction is small enough in order not to destroy the proton wavefunction when the pomeron is emitted. This is similar to an argument in ref. [20] where the proton is pictured as a disc and diffractive scattering is claimed to take place at the edge of the disc in order to keep the proton wavefunction intact. It is therefore natural to associate a small interaction radius with the pomeron.

To get a quantitative estimate of the pomeron radius we relate it to pomeron scattering cross-sections using an optical model which treats a particle as a disc giving the geometrical relation $\sigma \sim \pi R^2$. Based on the assumption of factorisation between different pomeron vertices, the pomeron–proton total cross-section can be extracted from a Regge analysis [21,7] of elastic and single diffractive cross-section data. The resulting value of about 1 mb is much smaller than the proton–proton cross-section and therefore shows the smallness of the pomeron radius compared to the proton radius of 0.8 fm. This proton radius is obtained from a proton–proton total cross-section of around 40 mb, which apply at intermediate energies, using $\sigma_{\mathrm{tot}} = 2\pi R^2$ and it agrees with the more properly defined proton radius obtained through a form factor analysis at non-relativistic energies.

Since the geometrical interpretation is simplified in the case of two identical particles, we consider the pomeron–pomeron cross-section $\sigma^{\mathrm{tot}}_{\mathrm{PP}}$. Based on Regge theory this cross-section [21,22] is related to the triple pomeron vertex and can therefore obtained from data on diffractive dissociation giving $\sigma^{\mathrm{tot}}_{\mathrm{PP}} \approx 0.14$ mb [22]. The pomeron–pomeron cross-section also enters as a factor in the cross-section given by Regge theory [21,22] for the double pomeron exchange process, which contains an effective pomeron–pomeron collision. From the double pomeron exchange cross-section, which has been calculated based on its relation to other diffractive processes [23] and measured [24], one can thus extract the pomeron–pomeron cross-section. These different methods to obtain $\sigma^{\mathrm{tot}}_{\mathrm{PP}}$ give consistent results varying between 0.1 and 0.2 mb. From the ratio of the pomeron–pomeron to the proton–proton cross-section we can therefore conclude, independently of the proportionality factor between cross-section and squared radius, that the pomeron should be at least a factor 10 smaller than the proton, i.e., the pomeron radius should not exceed 0.1 fm. However, there is still some uncertainty in this optical analogy since the pomeron need not have the same "blackness"as the proton. Thus, the small pomeron cross-section may partly result from a larger "transparancy"and not only from a smaller size.

In the following we will use $R = 0.1$ fm $= 0.5$ GeV^{-1} as a representative value for the pomeron radius. We note that it is in fair agreement with the value $\frac{1}{6}$ fm used in an analysis of exclusive ρ-production in DIS [25]. With the pomeron a factor 10 smaller than the proton, the non-linear term in eq. (1) should be enhanced by a factor 100. An additional enhancement comes from the large gluon content, which also enters squared. This increase is partly compensated by the fact that not so small momentum fractions can be reached in the pomeron as in the proton. In ep collisions the range of Bjorken-x is given by the scattered electron and should be the same for normal DIS and diffraction. Therefore, the relevant values of z in eq. (1) applied to the pomeron is at least an order of magnitude larger than x, since

$$z = x/x_{\mathrm{P}}, \tag{2}$$

where the pomeron should take a fraction $x_{\mathrm{P}} < 0.1$ of the proton momentum to ensure the diffractive nature of the scattering.

To make numerical estimates based on eq. (1) we need to specify the gluon distribution in the pomeron. Since this is a major uncertainty we illustrate its influence on the results by using as an Ansatz both a soft gluon distribution

$$z\,g(z,Q_0^2) = 6(1-z)^5 \tag{3}$$

and a hard one

$$z\,g(z,Q_0^2) = 2(1-z)\,, \tag{4}$$

where we have chosen $Q_0^2 = 10\ \text{GeV}^2$. This is also in line with earlier investigations of the pomeron structure [1,10]. The soft distribution corresponds to the pomeron as a many-gluon system and has some support from experiment as mentioned, although a more recent UA8 analysis seems to favour a harder distribution [26]. The hard distribution, eq. (4), would apply for a pomeron with fewer gluons and, being smaller at small z, could take into account possible gluon recombination effects already in the starting distribution [15]. It should be noted that the initial distribution is accessible to experimental measurements and this uncertainty can therefore eventually be removed. We note that the normalisation of these distributions is based on the assumption that the momentum sum rule is fulfilled, i.e.,

$$\int_0^1 dz\, z\,g(z,Q_0^2) = 1\,. \tag{5}$$

Although this seems reasonable and can be given some motivation [7] it is by no means clear that this relation must hold [12,11,26].

Starting with a gluon distribution that fulfills the momentum sum rule in eq. (5) at Q_0^2, the evolution in Q^2 will result in a lower value of the gluon momentum integral at a higher Q^2. The linear evolution conserves momentum, but since we here allow the process $g \to q\bar{q}$ some momentum is transferred to quarks. For example, at $Q^2 = 50\ \text{GeV}^2$ the linear evolution has reduced the gluon momentum integral to 0.86 (0.89) for the soft (hard) distribution. The non-linear evolution term does not conserve momentum and this cannot simply be attributed to the neglect of quarks. This term is in fact an approximation valid only at small x and therefore momentum conservation cannot be taken into account explicitly. For this reason we have applied an upper cut-off on the integral which we have chosen to be $y_{\max} = 0.1$ but our results do not depend sensitively on this. The inclusion of the non-linear evolution term results in a gluon momentum integral of 0.74 (0.86) for the soft (hard) distribution at $Q^2 = 50\ \text{GeV}^2$. Although this momentum loss is a non-negligible theoretical problem, it has no serious consequences for the main results and conclusions in this paper since it is likely to be compensated at large x, i.e., in a region which is of little interest in our study.

In fig. 2 we compare the initial gluon distributions with those evolved to $Q^2 = 50\ \text{GeV}^2$ (chosen large enough to give a sizeable effect and still within the reach of HERA) using standard linear evolution alone and with the inclusion of the non-linear term, i.e., eq. (1). Fig. 2a corresponds to gluon distributions in the pomeron, as discussed above, and fig. 2b to the gluon distribution in the proton which we have taken as $xg(x) = 4.5\,(1-x)^8$ at $Q^2 = 10\ \text{GeV}^2$ [27].

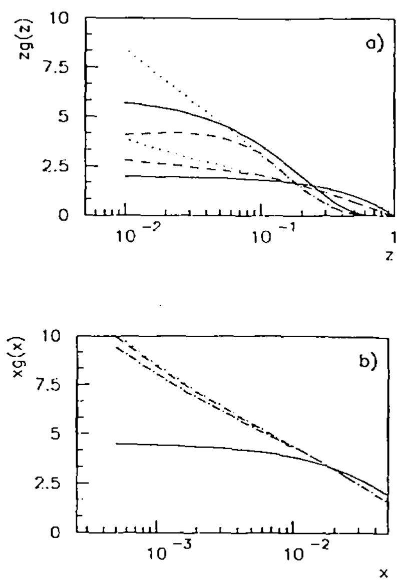

Fig. 2. The x-dependence of the gluon distributions in the pomeron (a) and in the proton (b). The initial distributions at $Q^2 = 10\ \text{GeV}^2$ (full lines) are evolved with QCD to $Q^2 = 50\ \text{GeV}^2$ using standard Altarelli–Parisi (dotted lines) and using the complete eq. (1) including the non-linear term (dashed curves). For the pomeron the upper three curves are based on the initial distribution $zg(z) = 6(1-z)^5$ and the lower curves on $zg(z) = 2(1-z)$, whereas for the proton the initial distribution is $xg(x) = 4.5(1-x)^8$. The non-linear evolution for a proton dominated by hot spots, as discussed in the text, is shown with a dashed-dotted line. The momentum fractions z in the pomeron and x in the proton are related by $z = x/x_{\mathbb{P}}$ and the pomeron momentum fraction $x_{\mathbb{P}} = 0.05$ is taken into account in the horizontal scales to facilitate a direct comparison.

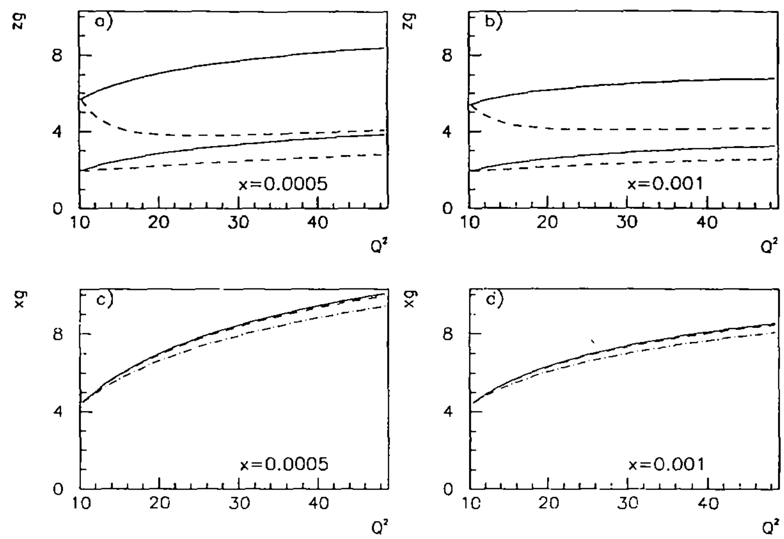

Fig. 3. The Q^2-dependence of the gluon distributions in the pomeron (a), (b) and the proton (c), (d) for $x = 5 \times 10^{-4}$ (a), (c) and $x = 1 \times 10^{-3}$ (b), (d). The curves describe linear (full) and non-linear (dashed) evolution as well as the case of hot spots in the proton (dash-dotted). Initial distributions and choice of $x_{\mathbb{P}}$ as in fig. 2.

Similarly, we show in fig. 3 the Q^2-dependences at two x-values. In order to compare the gluon distributions in the pomeron and in the proton we have used $x_{\mathbb{P}} = 0.05$, i.e., centrally in the diffractive region $x_{\mathbb{P}} < 0.1$, such that the momentum fraction z in the pomeron can be translated to $x = \frac{1}{20}z$. These figures demonstrate very clearly the large non-linear effects that arise in the pomeron. Even with the hard gluon distribution, which gives a smaller effect in absolute terms, it is still much larger than the corresponding effect on the gluon distribution in the proton. In relative terms the reduction of the gluon distribution is $\sim 40\%$ ($\sim 20\%$) at $x = 10^{-3}$, i.e., $z = 2 \times 10^{-2}$, and $Q^2 = 50$ GeV^2 for the soft (hard) gluon distribution in the pomeron. This should be compared with $\sim 1\%$ in the proton under normal conditions, but could become $\sim 6\%$ if the hot spot scenario turn out to be valid such that an effective radius of $R = 2$ GeV^{-1} should be used in eq. (1). Thus, also the hot spot hypothesis leads to smaller non-linear effects than should occur in a gluon-dominated pomeron with a small size as discussed above.

In case of the pomeron, the size of the non-linear term tend to become so large that one may in fact question the applicability of eq. (1). One would expect eq. (1) to become unreliable when the non-linear term is larger than the linear one, since this indicates that further correction terms or non-perturbative effects could be of importance. Even if the limit where eq. (1) ceases to provide an adequate approximation is not clear, it seems that this limit must be present somewhere in the kinematical region considered here since it covers both the region where the non-linear term is negligible and where it is larger than the linear term. Thus, it should be possible to determine experimentally at HERA where eq. (1) is applicable and, in addition, get information concerning the region beyond. This should add new insights to the problem of QCD at small x.

Whereas the effect of the non-linear term in the proton structure function may not be large enough to be clearly observable at HERA, it seems that the larger effect in the pomeron should be observable. Preliminary results from an ongoing study [28], where the gluon distribution of this paper is turned into an F_2 structure function for the pomeron, indicate that the diffractive ep cross-section is large enough to give useful statistics and sensitive enough to show the effect of the non-linear evolution.

To conclude, we have assumed that the pomeron is dominantly composed of gluons and argued that it has a considerably smaller size than a proton. Given this, we have estimated the perturbative QCD evolution of the gluon distribution in the pomeron and demonstrated the importance of the non-linear screening effects due to gluon recombination. These small-x effects have been predicted for the proton structure function, but not yet verified experimentally. We have found that they are much larger in case of the pomeron and may be observed for the first time in diffractive ep scattering at HERA. Our aim has not been to give accurate numerical predictions, in fact there are several uncertainties as pointed out, but rather to introduce and give the main expectations for a new process where the novel non-linear QCD effects at small x can be investigated.

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