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Signals of gluon recombination in deep inelastic scattering

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Abstract. The notion of a pomeron structure function arises in a model of electromagnetic diffractive scattering based on Regge factorization. Due to its small size we expect gluon recombination to occur significantly in the pomeron. The latest data from H1 (1999) show a Q^2 evolution in qualitative accordance with the GLR-MQ equations; these are the DGLAP (Altarelli–Parisi) equations corrected for the effect of gluon recombination.

1 Introduction

Some time ago a proposal was published to look for gluon recombination in deep inelastic diffractive scattering [1]. It was shown that the HERA accelerator provides experiments accurate enough for this process. A framework was worked out based on certain key assumptions (Fig. 1).
(1) The process occurs through an exchange of a color singlet particle, e.g. a pomeron.
(2) Regge factorization is valid, i.e. the electron–pomeron and the pomeron–proton interactions are independent of each other.
(3) The electron–pomeron subprocess factorizes into a perturbative and a non-perturbative part in analogy with inclusive scattering.
(4) The Q^2 evolution of the pomeron structure function is described by a QCD evolution equation.

Using this framework it was argued that gluon recombination should occur in the pomeron to an extent clearly measurable, which was not expected for the nucleon. The main reasons for this are twofold: Firstly the pomeron was assumed to be a pure gluonic object, its quark content being solely a result of the virtual fluctuations of a gluon into a quark–antiquark pair. Secondly and most important, its size could be concluded to be less than 1/10 of the nucleon.

Both experiments at HERA (H1 and ZEUS) have widely used this framework and H1 has applied the DGLAP evolution equations to the extracted pomeron structure function [2]. However, there has so far not been any attempt to explore the data for signs of gluon recombination. With the new data presented in 1998 and 1999 [3] it is worthwhile to direct the analysis with this ambition.

In this paper we will reexamine the framework, discuss the signature of gluon recombination and finally give a simple and qualitative interpretation of the new data. Our main point is the observation that the new data on the pomeron structure function exhibit undoubtedly an important effect, normally denoted “higher twist”. Occurring at low x and low Q^2 and with a negative sign it is naturally identified as gluon recombination, as predicted in [1]. We will not show a full QCD analysis of the data in this paper. Such an analysis is not at all necessary to point out the effect, since it is so clearly visible directly from the data. Instead we intend to do this when data have become more accurate and established, and we encourage other people to do so. One then also learns more about the pomeron size and its gluon content.

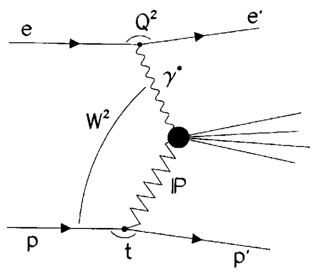

Fig. 1. Lowest order diagram of electromagnetic diffractive scattering with exchange of a single pomeron

2 The verification of the model

Since the original proposal was made new supporting evidence of the model outlined above has become available.

In 1992 ZEUS discovered electromagnetic diffractive scattering through the observation of rapidity gaps in the event structure of the final state [4].

H1 has given experimental support to the factorization assumption (point (2) above) [2], although at large momentum carried by the exchange particle the simple pomeron model needs correction. This is achieved by introducing an additional exchange particle in full accordance with Regge theory. The fact that the Regge trajectories found for these particles coincide well with the previously

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measured ones is an additional verification of the assumption made here.

Theoretically, there is strong support given by Collins [5]. He showed in 1997 that factorization holds within QCD for hard electromagnetic diffraction so that QCD evolution applies to the pomeron structure function, verifying point (3) and (4) above.

Concerning the nature of the pomeron, H1 made a QCD analysis of its measured structure function based on the DGLAP evolution equations and found that the pomeron indeed is gluon dominated [2]. Furthermore, the important size formula used originally to obtain the pomeron size [1] has got support in a derivation based on more fundamental concepts [6]. Both find that the hadron–hadron cross section is proportional to the hadronic squared size, although different kinds of processes are considered[1]. However, the pomeron size is still uncertain and more information will be gained from a full QCD analysis of its structure function. As pointed out above, time is unfortunately not yet ready for such a work since both data and theory need to be more established.

Thus, the assumptions and the intuitive treatments presented originally in [1] are now well verified both experimentally and theoretically. This opens up new horizons for the physics community. Through electromagnetic diffractive scattering we obtain a laboratory for unique studies of gluon dynamics at high density. New, really fundamental processes such as gluon recombination are then expected to occur. The importance of these studies for our ultimate understanding of QCD cannot be overestimated. Gluon recombination, for example, is the simplest and the only theoretically controlled higher twist effect and therefore would have importance for our interpretation of confinement. Higher twist effects occur in the theory of operator product expansions and are understood as parton–parton interactions, i.e. longer distance effects than what is taken into account in the DGLAP equations. Such effects naturally would play an essential role in the confinement build-up.

3 QCD evolution with gluon recombination

Gribov, Levin and Ryskin originally showed how to qualitatively modify the DGLAP gluon evolution equation in order to incorporate effects of gluon recombination [7]. Mueller and Qiu later completed the equation numerically and also derived the equation for the conversion of gluon to quarks, an achievement of considerable importance since they thus provide the link to experiments. We state here their results, which we denote as the GLR-MQ equations

$$\frac{\mathrm{d}G(\beta,Q^2)}{\mathrm{d}\log Q^2} = \frac{\alpha(Q^2)}{2\pi}\beta\int_\beta^1 \frac{\mathrm{d}y}{y^2}G(y,Q^2)P_{gg}\left(\frac{\beta}{y}\right) - \frac{81\alpha_s^2(Q^2)}{16R^2Q^2}\int_\beta^1 \frac{\mathrm{d}y}{y}[G(y,Q)]^2, \quad (1)$$

$$\frac{\mathrm{d}\beta q(\beta,Q^2)}{\mathrm{d}\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\beta\int_\beta^1 \frac{\mathrm{d}y}{y^2}G(y,Q^2)P_{qg}\left(\frac{\beta}{y}\right) - \frac{27\alpha_s^2(Q^2)}{160R^2Q^2}[G(\beta,Q^2)]^2 + \mathrm{HT}. \quad (2)$$

The notation is as follows: in the infinite momentum frame we interpret $\beta\mathfrak{g}(x)$ as the fraction of the pomeron (proton) momentum carried by the struck quark. These are related through the relation $\beta\cdot X_\mathrm{P} = x$, where X_P is the fraction of the proton momentum carried by the pomeron. $q(\beta,Q^2)$ is the quark density, the Ps are the splitting functions and Q^2 is the virtuality of the exchanged photon[2]. HT denotes a further term notified by Mueller and Qiu but not fully given. It was neglected in the calculations presented below. We also neglect the quark gluon emission diagrams due to their little importance in the gluon rich low-x region.

We note the size parameter R in the denominator and the gluon distribution G in the numerator of the second terms on the right hand side. Since these terms enter the recombination terms squared they are crucial for the magnitude of the effect. As argued above, the pomeron is dominated by gluons and has a small size leading to large effects of gluon recombination. Solely because of its size, being at least 10 times smaller than the nucleon, the gluon recombination terms are enlarged a factor of at least 100 compared to the nucleon. How could gluon recombination be detected?

Since gluon recombination introduces a negative correction to the DGLAP evolution equations the signal of its presence is a decrease of the scaling violations as compared to the expectations obtained from the DGLAP equations. In the DGLAP scheme we expect a fairly constant value of $\mathrm{d}F_2/\mathrm{d}\log Q^2$ or a slight *increase* of $\mathrm{d}F_2/\mathrm{d}Q^2$ when Q^2 *decreases* (Fig. 2a). However, if gluon recombination is strongly present, the GLR-MQ equations predict a *decrease* of $\mathrm{d}F_2/\mathrm{d}Q^2$ (as well as of $\mathrm{d}F_2/\mathrm{d}\log Q^2$) when Q^2 *decreases* (Fig. 2b). Although two radically different gluon distributions were considered (Fig. 3) we arrive at the same conclusion. In Fig. 2 $\mathrm{d}F_2/\mathrm{d}Q^2$ is obtained from (2) by summing quark distributions weighted by squared charges, as usual.

It is clear from Fig. 2 that if gluon recombination plays an essential role in the gluon dynamics it is easy to discover, since it gives such a radically different expectation on well measured quantities as compared to the well established DGLAP dynamics.

[1] In this context the concept of size refers to the transverse dimension, i.e. to a direction perpendicular to the momentum of the exchange boson (the photon in this case).

[2] Note that the GLR-MQ equations do not conserve momentum. This follows from the fact that the correction terms to the DGLAP equations are single-signed (negative). Fortunately, this problem has been solved [9] by introducing a corresponding antirecombination effect (antishadowing) occurring at larger values of β. It has been shown [10] that this effect is small in the region considered here.

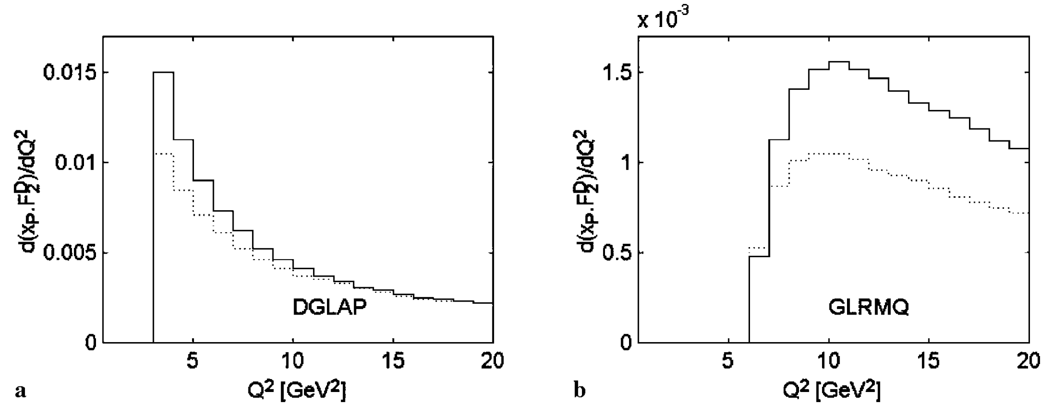

Fig. 2a,b. The calculated Q^2 derivative of the renormalized diffractive structure function, $x_{\rm P} \cdot {\rm d}F_2^{\rm D}/{\rm d}Q^2$, for $\beta = 0.04$ The QCD parameters $\Lambda = 200\,{\rm MeV}$ and the number of quark flavors $n_f = 4$. The calculation was done in leading order. Broken (full) lines were obtained using initial gluon distributions at $Q^2 = 3\,{\rm GeV}^2$ described by broken (full) lines in Fig. 3. **a** Linear evolution according to the DGLAP equations. **b** Non-linear evolution according to the GLR-MQ equations. The minimum Q^2 value of the calculation was $3\,{\rm GeV}^2$ so that saturation is reached at $Q^2 = 5\,{\rm GeV}^2$ in this case. The pomeron size parameter $R = 0.5\,{\rm GeV}$, i.e. 1/10 of a nucleon. This value was concluded to in [1] after an analysis of different diffractive processes

A so-called saturation effect occurs if the contribution from gluon recombination is so strong that the scaling violations disappear, i.e. ${\rm d}F_2/{\rm d}\log Q^2 = 0$. In such a case, (1) and (2) should be used with caution since further higher twist terms might then be of importance. Their predictive power should under all circumstances at least be considered as indicative.

4 The measured pomeron structure function

In 1997 H1 presented the first measurement of the pomeron structure function $F_2^{\rm Pom}$ ever[3] [2]. Positive scaling violations were found for all values of β. This is expected for a gluon dominated particle and the succeeding QCD analysis, based on the DGLAP equations, confirmed this interpretation.

In 1998 H1 had analyzed new data and presented results on the pomeron structure function in an extended kinematical range [3] (see Fig. 4).

In particular, the new data at low β and low Q^2 are interesting for this discussion. At fixed and low β they observe a remarkable decrease of the scaling violations with decreasing Q^2, as can be seen clearly in the bins $\beta = 0.04$, 0.1 and 0.2. Attempts by H1 to fit DGLAP predictions to these data fail [11]. The reason is that the new data (triangles), occurring at $Q^2 < 6\,{\rm GeV}^2$, show a Q^2 dependence which is apparently smaller than at $Q^2 > 6\,{\rm GeV}^2$ (squares). Thus, this is not compatible with DGLAP expectations but harmonizes well with the general predictions from the GLR-MQ equations, as can be seen in Fig. 2.

Actually, since there are good reasons to believe that we here observe effects from gluon recombination, its contribution to the gluon dynamics is so large that saturation, i.e. ${\rm d}F_2^{\rm Pom}/{\rm d}Q^2 = 0$, seems to have been reached. In the bins $\beta = 0.04$, 0.1 and 0.2 there are indications of this effect somewhere between $Q^2 = 4$ and $Q^2 = 10$, but we cannot conclude as to exactly where.

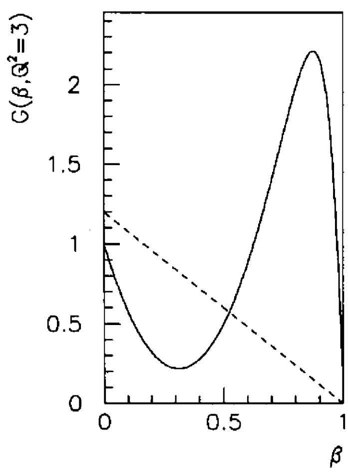

Fig. 3. The initial gluon distribution at $Q^2 = 3\,{\rm GeV}^2$ used to obtain the result in Fig. 2. The full line is a distribution similar to that found by H1 [2]. The broken line is a more normal distribution given by $G = 1.2(1 - \beta)$. By using these two radically different functions, our ignorance of its actual shape is taken into account

Indeed, according to Fig. 2 we do expect saturation to occur in the region of measurement if the pomeron model outlined above is valid. In Fig. 2 saturation is reached at $Q^2 = 5\,{\rm GeV}^2$ but we stress that our aim with this calculation is just to point out the general trend of data expected from the two different analyses.

Nevertheless, just for illustrative purposes, we can pursue the comparison with data by calculating the absolute value of $F_2^{\rm D}$ from the derivatives in Fig. 2 fixing the nor-

[3] Although hints on its parton distribution had been obtained before from strong interaction scattering this was the first direct measurement of the pomeron F_2.

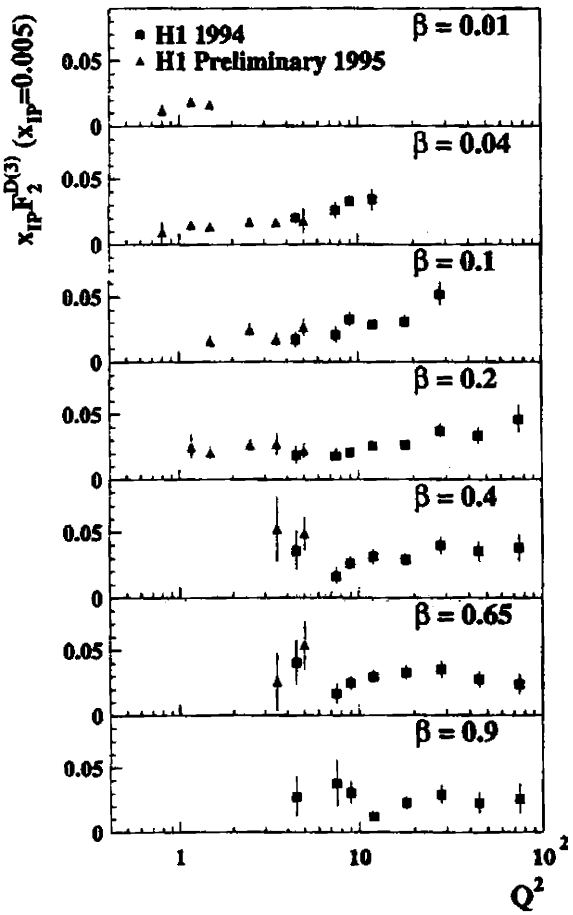

Fig. 4. Experimental result on the pomeron structure function as obtained by H1 [3]. The interesting observation is that the bins $\beta = 0.04$, 0.1 and 0.2 exhibit a Q^2 derivative which is smaller at $Q^2 < 6\,\mathrm{GeV}^2$ than for data at $Q^2 > 6\,\mathrm{GeV}^2$. This is not compatible with DGLAP expectations

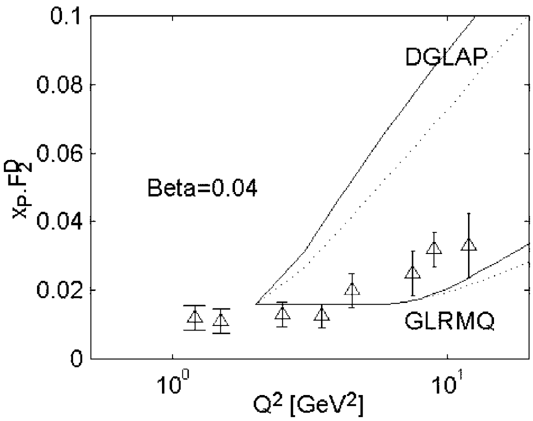

Fig. 5. A qualitative comparison between theory and data at βg0.04. The predicted F_2^{D} was normalized so that $x_P F_2^{\mathrm{D}}(Q^2 = 2) = 0.016$ to optimize the accordance with the data

malization according to the data[4]. Figure 5 shows the result for $\beta = 0.04$ only, which, however, must be considered just as a qualitative investigation.

Three important qualities which rule out the DGLAP dynamics can thereby be noted again.

(1) DGLAP gives an order of magnitude larger derivative than what is observed.

(2) DGLAP cannot account for the saturation effect which is visible in the data.

(3) DGLAP predicts an increasing Q^2 slope with decreasing Q^2, which contradicts the observation.

On the other hand, the GLR-MQ dynamics accounts for all the above three points.

Therefore, we claim here that the data exhibit the presence of a higher twist term with a negative sign of which the importance increases with decreasing β. The magnitude of the term is large at low β, but it is not likely that it can be neglected anywhere in the measured kinematical region. This was done by H1 in their first analysis [2] but hopefully they will reanalyze the data with a higher twist term included. Since scaling violations are directly proportional to parton densities, this would certainly yield a completely different gluon distribution. After all, the H1 result, fit 3, on the gluon distribution presented in [2] and which is sketched approximately in Fig. 3 is unexpected for a hadron.

Finally, one should also bear in mind the fact that the fraction of diffractive events increases rapidly with decreasing Bjorken variable x. Since diffractive events exhibit smaller scaling violations than the non-diffractive events (presumably due to gluon recombination) we expect an interesting effect in case of inclusive (no selection) scattering: At low x, diffraction starts to significantly contribute to the event sample which would show up as a decreasing Q^2 dependence with decreasing x. Indeed, this is what is observed [12]; this came as a general surprise to the community, basing their expectations on the familiar DGLAP equations.

5 Summary and prospects

Our aim in this paper was first to make clear that the notion of a pomeron structure function, measurable and treatable in QCD, now rests on solid experimental and theoretical grounds. As in the case of the nucleon structure function it is its Q^2 evolution that gives safe information concerning the basic structure and dynamics of the object.

Secondly, we pointed out interesting features in the recently experimentally determined pomeron structure function. Its Q^2 evolution is not compatible with the ordinary DGLAP equations but instead is in qualitative accordance with the GLR-MQ equations. This would mean that effects of gluon recombination are present in the process. We stress, though, that both theory and experiment are in its infancy so that a more solid statement would be that a higher twist effect with a negative sign has been observed. Consequently, although a numerical analysis is presented in Fig. 2, the result should be used only qualitatively when compared to the experimental data in Figs. 4 and 5.

[4] F_2^{D} is the diffractive structure function which factorizes into a pomeron flux times the pomeron structure function; see [1,2].

More data, which steadily arrive from the HERA experiments will increase the precision and presumably extend the kinematical range, giving us a unique opportunity to thoroughly study QCD in a new way.

HERA is the only place in the world where measurements of this kind can be done. Apart from the pomeron one could also try to study for example the pion in the same way but identifying a neutron in the final state instead. Apart from eventually validating the above mentioned procedure one could then also gain insight in new aspects of QCD since the pion is very different from both the pomeron and the nucleon.

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