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Antishadowing Contribution to the Pomeron Structure Function

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Abstract. In a particular model of the pomeron, its gluon and quark distributions are subject to anti-shadowing, as described by a modified GLR equation recently derived. Inclusion of antishadowing cures the problem of momentum non-conservation previously existing in the GLR equation. A possible outcome of a measurement of the pomeron structure function at HERA is shown in case of DGLAP, GLR and modified GLR parton dynamics.

1 Introduction

The application of perturbative QCD to structure functions constitutes one of the most quantitative tests of QCD. Whereas most of the interest has centered around the nucleon, which is easiest to investigate, structure functions of other particles could equally well serve as interesting tests of QCD. Indeed, although the electron-proton colliding machine HERA is in full operation, planned measurements of nucleon structure functions might very well not explore new physics but instead just improve the accuracy of parton distributions and the strong coupling which is of course highly valuable. On the other hand, measurements of non-nucleon structure functions might reveal new phenomena since the investigations done so far are sparse and not so accurate. Thus, at HERA it has been proposed to study the structure function of the pion [1] as well as that of the pomeron [2]. An accurate QCD application of these structure functions would be very interesting since the parton content of the pion is so different compared to the nucleon and the pomeron is likely to be a pure gluon state, i.e. a glueball. In addition, it has been argued that the pomeron has a very small size [3] and therefore one expects gluon recombination as described by the GLR equation [4] to occur frequently. This argument could also apply to the pion, whose strong interaction size might be small.

This kind of measurement is proposed to be realized through a tagging of the leading outgoing nucleon of the final hadronic state, a proton (neutron) in case of the pomeron (pion). A virtual beam of pomerons (pions) is then created which interact with the electrons. At HERA, detectors to tag both the leading proton and the neutron are in operation.

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As a word of caution, the exchanged particles are not on-shell so the decomposition of the cross section in terms of the usual structure functions might not apply. In this paper we shall assume the normal F_2 structure function to dominate the cross section and we shall only deal with the pomeron structure function and return to the pion case in future works.

As is obvious from above, we consider the pomeron as a particle. Although this concept is controversial, we find it otherwise hard to introduce a structure function, understand the factorization property used below and to apply the parton model on the pomeron. Thus, in the approach presented in this paper, the particle concept of the pomeron is hard to avoid but one should bear in mind different approaches where this concept is not needed [5].

The main aim of this paper is to investigate if a new interesting phenomena, anti-shadowing [6], is detectable through the measurement of the pomeron structure function at HERA. We therefore repeat and update the formalism worked out in [7] for the pomeron phenomenology appropriate for extracting its structure function. There are many uncertain parameters needed to do quantitative predictions and the result obtained here should only be taken as indicative. However, we emphasize below the many possibilities that exist through the HERA experiments to learn more about the pomeron and to test the correctness of the assumptions made here.

2 Gluon Recombination and Anti-Shadowing

The present data on the Q^2 evolution of structure functions is well described by perturbative QCD as predicted by the DGLAP [8] equations. However, at lower x an additional process is expected to contribute significantly to the QCD evolution, namely gluon recombination. The GLR equation [4] takes this into account by correcting the DGLAP equation by a negative term quadratic in the gluon density g, i.e.

$$\begin{aligned} \frac{\partial zg(z,k^2)}{\partial \ln k^2} &= \frac{\alpha_s(k^2)}{2\pi} z \int_z^1 \frac{dy}{y^2}\, yg(y,k^2) P_{gg}\left(\frac{z}{y}\right) \\ &- \frac{81\alpha_s^2(k^2)}{16R^2k^2}\theta(z_0-z)\int_z^{z_0}\frac{dy}{y}\left[yg(y,k^2)\right]^2 \end{aligned} \qquad (1)$$

where $zg \equiv G$ is the gluon distribution, z the fractional momentum carried by the gluon, k^2 the virtuality of the probed gluon, P_{gg} the DGLAP pure gluon kernel and R the size of the studied object. z_0 was introduced in order to prevent contributions at too a large value of y [9]. This equation was also derived in ref. [10].

Due to the negative sign of the correction term the gluon density is reduced, compared to a solely DGLAP evolution, as expected since this would be an effect of gluon recombination. Therefore, this kind of correction is sometimes called 'screening' or 'shadowing'. However, as a consequence, eq. (1) doesn't conserve momentum, which has been explicitly demonstrated in case of the pomeron structure function [7] where large effects from gluon recombination are expected.

A way out of this problem was presented in [6]. The idea is that gluon recombination should not only give rise to a reduction of the gluon density but also to an enhancement effect (also called anti-screening or anti-shadowing) at some larger momentum. Taking this into account the new equation is [6]

$$\begin{aligned}
\frac{\partial zg(z,k^2)}{\partial \ln k^2} &= \frac{\alpha_s(k^2)}{2\pi} z \int_z^1 \frac{dy}{y^2}\, yg(y,k^2) P_{gg}\left(\frac{z}{y}\right) \\
&- \frac{81\alpha_s^2(k^2)}{16R^2k^2} \int_z^{z_0} \frac{dy}{y} \left[yg(y,k^2)\right]^2 \\
&+ \frac{81\alpha_s^2(k^2)}{16R^2k^2} \int_{z/2}^{z} \frac{dy}{y} \left[yg(y,k^2)\right]^2 \\
& if\ z \leq z_0 \\
\frac{\partial zg(z,k^2)}{\partial \ln k^2} &= \frac{\alpha_s(k^2)}{2\pi} z \int_z^1 \frac{dy}{y^2}\, yg(y,k^2) P_{gg}\left(\frac{z}{y}\right) \\
&+ \frac{81\alpha_s^2(k^2)}{16R^2k^2} \int_{z/2}^{z_0} \frac{dy}{y} \left[yg(y,k^2)\right]^2 \\
& if\ z_0 \leq z \leq 2z_0 \qquad (2)
\end{aligned}$$

which we denote as the 'modified GLR equation'.
In the nucleon, both the effect of shadowing and anti-shadowing have been shown to be small [6] within the kinematical region of HERA and constitute a great experimental challenge to be observed.

3 Pomeron Phenomenology

3.1 The diffractive cross-section and the pomeron structure function.

In this paper we investigate the effect of eqn. (2) w.r.t. the DGLAP and the original GLR equations for the case of parton dynamics inside the pomeron. We thereby continue the studies presented in [7] and [3] where it was shown, within some reasonable assumptions concerning the nature of electromagnetic diffraction and the structure of the pomeron, that gluon recombination is expected to be an important source for the evolution of the pomeron structure function. The main reason for this is the small size of the pomeron as argued there.
Being an exchange object in diffractive scattering, the pomeron has the quantum numbers of the vacuum. In phenomenological applications of diffraction with pomeron exchange some simplifying assumptions are usually made whose validity should finally be settled by experiments:

- The cross-section factorizes.
- The pomeron can be treated as an on-shell particle.
- The pomeron valence partons are gluons only.

We consider here diffractive subprocesses in ep collisions, as they are intended to be studied at the HERA experiments. From the first two assumptions above the deep inelastic lepton-pomeron process can be defined and hence the pomeron structure function as discussed in [7]. Although the assumptions above are used frequently they are certainly not free from objections. Indeed, the factorization property has been questioned by e.g. Frankfurt and Strikman [11], the particle treatment by e.g. Levin and Wüsthoff [5] and the pure gluon content of the pomeron by e.g. Donnachie and Landshoff [12]. Although these objections have to be taken seriously, we assume that in a first approximation the above simplifications can be made.
The cross-section is then given by [7]:

$$\frac{d\sigma(ep \to epX)}{dx_{I\!P}dtdxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}(1-y+\frac{y^2}{2})f_{I\!P/p}(x_{I\!P},t)F_2^{I\!P}(\frac{x}{x_{I\!P}},Q^2) \tag{3}$$

where $x_{I\!P}$ is the fractional longitudinal momentum carried away by the pomeron so that $z = x/x_{I\!P}$, $-t$ is the squared momentum of the pomeron and Q^2 is the virtuality of the exchanged photon. x is here the usual fraction of the proton momentum carried by the struck parton.
As a consequence of the assumed factorization property, the diffractive structure function is given as a product of the pomeron F_2 and the pomeron 'flux', $f_{I\!P/p}$. Other authors utilize the factorization property in a similar way [2, 12, 13, 14, 15] but propose differing forms for the pomeron flux (see next section).
An additional source of uncertainty comes from the initial parton distributions needed to predict the Q^2 evolution of structure functions. We assume here that the pomeron is purely gluonic, i.e. quarks can only exist through the QCD dynamics of the gluons. Although some momentum of the pomeron must therefore be taken up by quarks we neglect this small contribution and make use of initial gluon distributions saturating the momentum sum rule. There are some indications that this distribution is rather hard [17, 18, 19] but it depends of course on the momentum scale. Starting the evolution from a low scale we follow these indications and use two fairly hard ones proposed in the literature [2] [15]

$$G^{I\!P}(z,k_0^2) = 6z(1-z) \tag{4}$$

$$G^{I\!P}(z,k_0^2) = (0.18+5.5z)(1-z) \tag{5}$$

Within the framework presented above it should be noted that the gluon distribution of the pomeron can experimentally be constrained from the Q^2 evolution of the pomeron F_2. For instance, the approximate relation [20]

$$dF_2/dlogQ^2(z) \propto G(2z) \tag{6}$$

can be used at low-z. Even better is to make a full QCD analysis of the pomeron F_2 in analogy with the QCD application of the nucleon structure function.
We try here to predict, from a given initial gluon density, the measurable F_2 of the pomeron for the different cases of gluon dynamics. Having defined the pomeron flux (see below), the cross section is then determined and the statistical precision expected at HERA can be obtained. In this way, we aim for concluding whether anti-shadowing need to be taken into account at the HERA experiments. The uncertainty of the actual gluon distribution is considered by trying the two different distributions (4) and (5).
The parameter R, the size of the studied object, was set to 0.5 GeV^{-1}. This value was proposed in [7] obtained from an analysis of various cross section measurements of double

pomeron exchange in hadron-hadron scattering. This means that the pomeron is nearly 10 times smaller than the proton, magnifying the gluon recombination effect by a factor 100. z_0 was set to 0.2 corresponding to $x = 0.01$ (for $x_{I\!P} = 0.05$).

We proceed as follows: The gluon density is evolved with the DGLAP, GLR and the modified GLR equations to a particular value of k^2. Then the gluons have to be converted into quarks since leptons don't interact with gluons. In the language of ladder diagrams this is equivalent to having a chain of gluon loops in the bottom of the ladder and the last loop is the gluon to quark conversion. Neglecting quark loops in preceding steps is motivated at low-z since in leading order the singular property of the pure gluon splitting kernel $P_{gg}(z/y)$ makes the gluon splitting into gluons to dominate that into quarks. The last loop (gluon to quark conversion) is calculated in the DGLAP scheme, i.e. integrating the DGLAP equation w.r.t. Q^2 one has

$$q^{I\!P}(z, Q^2) = \int_{k_0^2}^{Q^2} \frac{dk^2}{k^2} \frac{\alpha_s(k^2)}{2\pi} \int_z^1 \frac{1}{y^2} G(y, k^2) P_{qg}(\frac{z}{y}) dy \tag{7}$$

where $q^{I\!P}(z, Q^2)$ is the quark distribution inside the pomeron. Gluon recombination in this step is neglected but is expected to be small, although not fully known [10]. Using (7) for this loop is consistent with the approximation scheme used in the preceding steps of the ladder. $F_2^{I\!P}$ is finally obtained by summing the charge- and z-weighted quark distributions over four flavours.

We note the infrared cut-off used in (7) necessary in order not to enter the non-perturbative region. Also, since the calculation was done in leading order, k_0^2 was set to 4 GeV^2. Experimentally, this cut-off need never enter since $dF_2/dlogQ^2$ can be extracted directly from the data and compared with the prediction, which is free from any cut-off. However, here we need the absolute F_2 in order to estimate the cross section and the statistical accuracy that can be achieved at HERA. Since the neglected tail below k_0^2 certainly contributes positively to $F_2^{I\!P}$ the obtained statistical accuracy is under-estimated.

3.2 Pomeron Flux

For the purpose of estimating the diffractive cross section at HERA and the possible statistical precision that can be achieved, the pomeron flux, $f_{I\!P/p}(x_{I\!P}, t)$, needs to be defined (see eq. (3)). We consider here four models of the pomeron flux, plotted in fig. 1. Whereas the $x_{I\!P}$ dependence for all models is inferred from Regge theory, the t dependence is fitted to UA4 data [21] for the model of Berger et al [15] as well as that used by Bruni and Ingelman [16]. On the other hand, the models of Badelek and Kwiecinski [13] and Donnachie and Landshoff [12] utilize the nucleon form factor containing most of the t dependence. As seen in fig. 1 the models differ markedly both in normalization and t dependence.

Assuming there is no t dependence of $F_2^{I\!P}$, we compare the predictions for the b-slopes, i.e the t dependence is parameterized in the following form

$$f_{I\!P/p}(x_{I\!P}, t) \propto e^{bt} \tag{8}$$

At $-t = 0.25$ GeV^2, the b-slopes are given in table 1 for the different models at various values of $x_{I\!P}$.

$x_{I\!P}$:	0.01	0.04	0.09
BI [16]	7.1	7.1	7.1
BK [13]	4.2	4.2	4.2
BCSS [15]	6.5	6.5	6.5
DL [12]	5.7	5.0	4.6

Table 1: b-slopes $[GeV^{-2}]$ at $-t = 0.25\ GeV^2$ obtained from different models of the pomeron flux.

Note that the Donnachie-Landshoff model is the only one exhibiting b-slopes depending on $x_{I\!P}$. Comparing the b-slopes with the measurement by NMC [22], it seems that only the Donnachie-Landshoff and Badelek-Kwiecinski models reproduce this result, i.e. $b = 4.3 \pm 0.6 \pm 0.7\ GeV^{-2}$ at $-t = 0.25\ GeV^2$. As we are considering electromagnetic diffractive scattering at high Q^2, like the NMC data, models reproducing the NMC measurement are most attractive. However, the normalization difference between these models is significant. We choose to use the flux proposed by Badelek-Kwiecinski, since their approach is more in line with our use of the factorization property. This means that the discrepancy between these models might be due to a different definition of the pomeron structure function. Thus,

$$f_{I\!P/p}(x_{I\!P}, t) = \frac{\sigma_{pp}^{I\!P} S_N^2(t)}{16\pi x_{I\!P}} \tag{9}$$

where $\sigma_{pp}^{I\!P}$ is the part of the proton-proton cross section corresponding to pomeron exchange, set to $100\ GeV^{-2}$, and $S_N = 1/(1 + |t|/t_o)^2$ is the nucleon form factor where $t_0 = 0.7\ GeV^2$ [13]. The exact form of this flux can further be studied at HERA through the $x_{I\!P}$ and t dependence of the diffractive cross section.

4 Results

To get an impression of the size of the different terms in eq. (2) we first study the pure gluon evolution. Fig. 2 shows the result using the two different initial distributions given above. We see the enhancement effect in both cases in the region $0.1 < z < 0.4$ (solid line) as compared to the DGLAP case (dashed line). Momentum is conserved for both the DGLAP and the modified GLR case but not for the original GLR equation (dashed-dotted line). The initial distributions (dotted lines) look quite similar but at low-z the difference is notable. The results of the evolution are quite similar, though.
Since the gluon distribution enters quadratically for the gluon recombination terms in eqs. (1) and (2), the magnitude of these terms is crucially dependent on the actual distribution. Indeed, a soft initial distribution of the type $G(z, k_0^2) = 2(1 - z)$ results in a gluon recombination effect which is larger in magnitude than the DGLAP term at low z and k^2. This is undesirable since the GLR equation was derived under the assumption that the contribution from gluon recombination is small. Therefore, at the moment, we conclude that if it turns out that the gluon distribution of the pomeron is much softer than those used here at $k^2 = 4\ GeV^2$, so that gluon recombination dominates over the DGLAP effects, then the GLR and modified GLR equations are not applicable to the

pomeron parton dynamics at this momentum scale. One should then try to look at the evolution at higher values of z and k^2 but then the experimental statistical precision will get worse. Fortunately, as mentioned above, there is experimental evidence of a rather hard gluon distribution in the pomeron [17, 19].

Finally, fig. 3 shows the result for the directly measurable pomeron F_2 using (7) to obtain F_2 from the gluon distribution. The statistical error bars correspond to a luminosity of $100\,pb^{-1}$. We see a small effect of enhancement (unfilled triangles) but it is just slightly statistically significant compared to the original GLR equation (filled triangles). Both eqs. (1) and (2) give, however, a clear significant different result at low-x as compared to the DGLAP evolution (circles). The result is almost identical for the two different input gluon distributions so we choose to show only the result from one.

In ref. [7] a different scheme was chosen for the gluon to quark conversion, giving a different result for $F_2^{I\!P}$. In this scheme the full dependence on the transverse momentum is taken into account. However, aiming for consistency between the gluon evolution and the gluon to quark conversion, eqn. (7) is a better choice. The failure of the 'co-linear' approximation is expected when reaching very low-x. However, in the process dealt with here, z is the relevant variable since the evolution equations are applied directly to the pomeron and don't involve the mother proton. But $z > 0.01$ so using the co-linear scheme is appropriate.

5 Summary

We have investigated effects on the pomeron gluon and quark distributions from '(anti)-shadowing'. At HERA, it will be hard to observe such a small effect of anti-shadowing as obtained here, although the effect is not negligible. The modified GLR equation, taking into account both shadowing and antishadowing doesn't change the original conclusion [7] that gluon recombination is an important source for the evolution of the pomeron structure function. We encourage, therefore, a search for gluon recombination in general by measuring the pomeron structure function as defined here and in given references.

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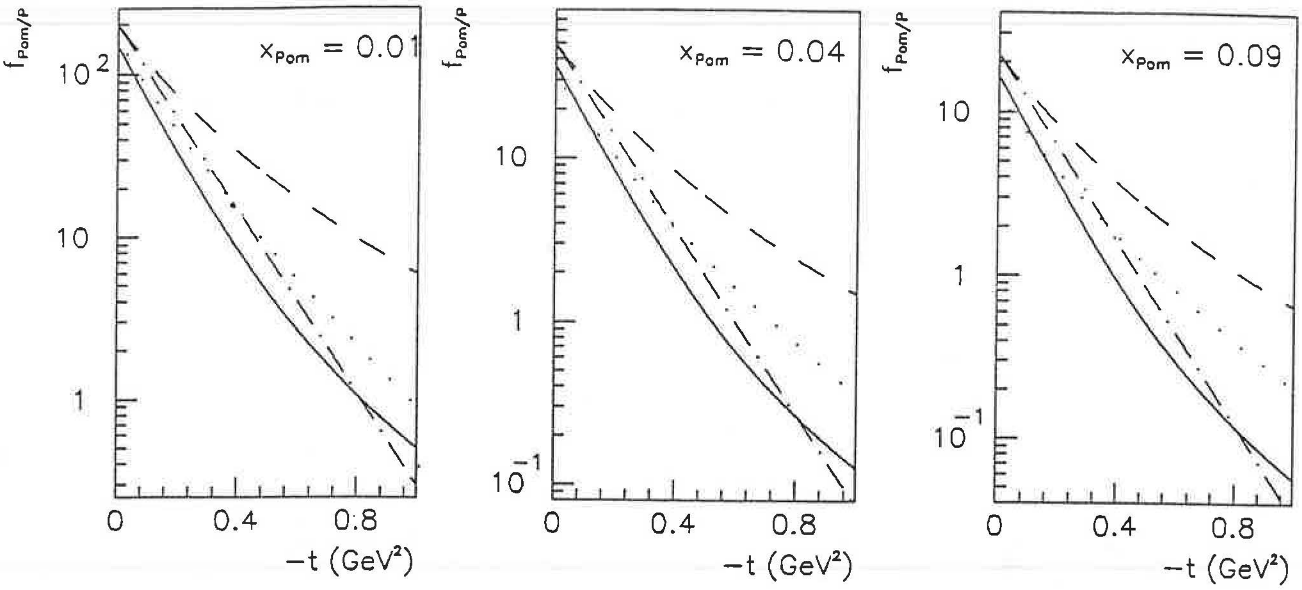

Figure 1: *The pomeron flux obtained from different models: Dotted: Donnachie-Landshoff [12]. Dashed-dotted: Berger et al. [15]. Dashed: Badelek-Kwiecinski [13]. Solid: Bruni-Ingelman [16]. The unit is* GeV^{-2}.

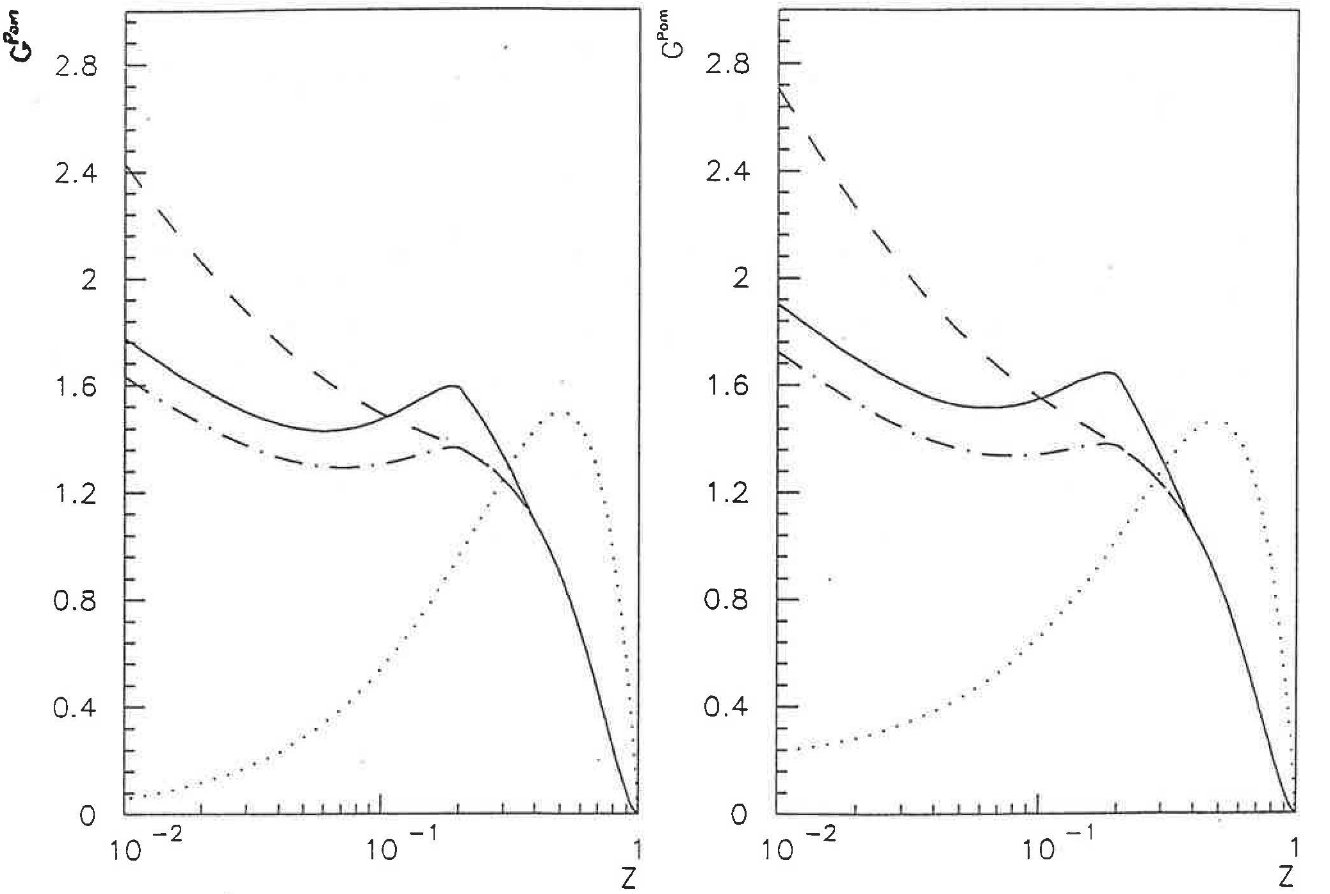

Figure 2: *The z dependence of the pomeron gluon distribution. z is the fraction of the pomeron momentum taken up by the gluon. The initial distribution (dotted line), given at* $k^2 = 4\,GeV^2$, *is evolved to* $k^2 = 50\,GeV^2$ *with the GLR equation (dashed-dotted line), the DGLAP equation (dashed line) and the modified GLR equation (solid line). The initial distributions were* $G(z, k_0^2) = 6z(1-z)$ *(left-hand plot) and* $G(z, k_0^2) = (0.18 + 5.5z)(1-z)$ *(right-hand plot).*

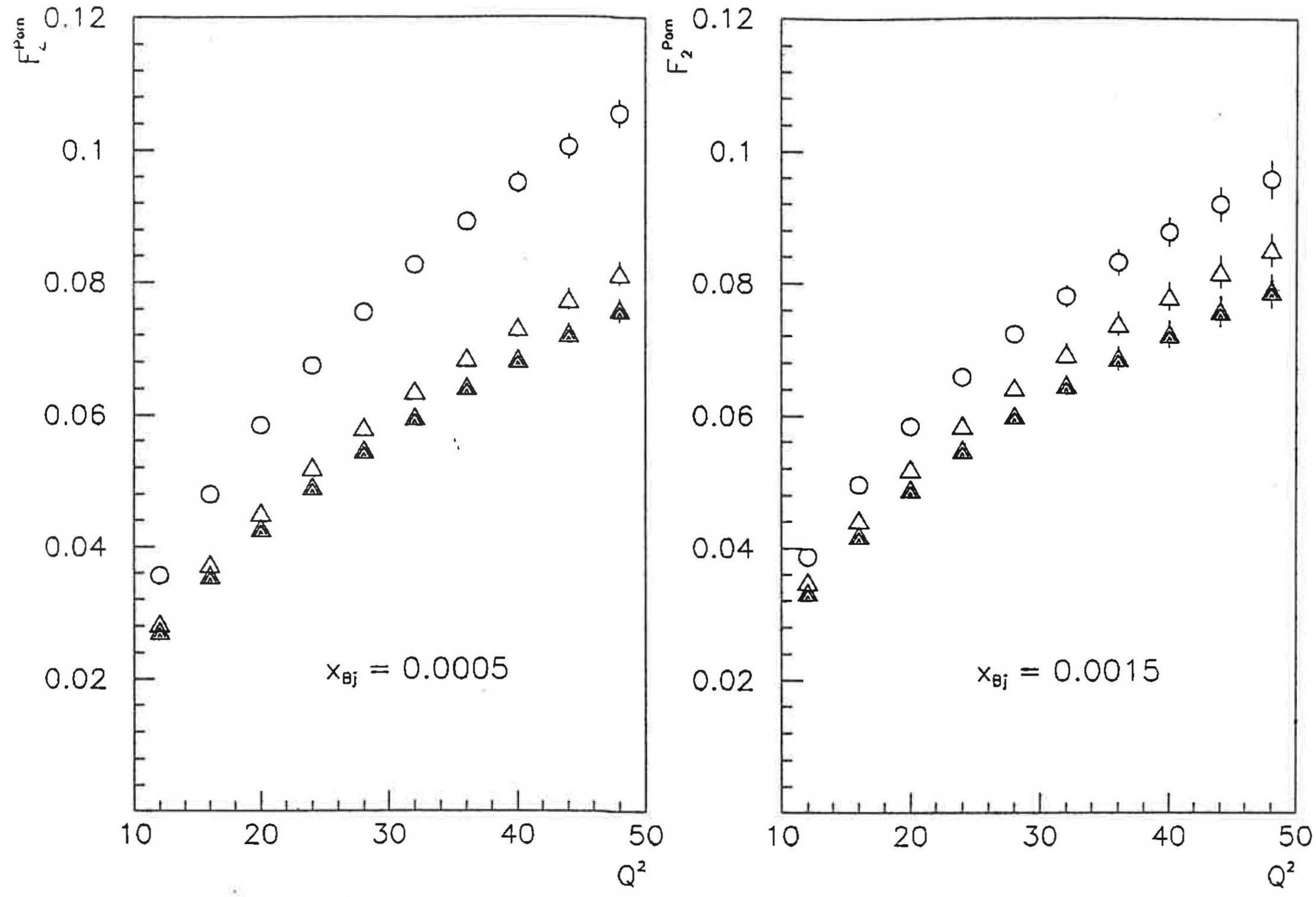

Figure 3: *The Q^2 dependence of the directly measurable pomeron F_2. The initial gluon distribution $G(z,k_0^2) = (0.18+5.5z)(1-z)$. The values of x, noted on the plots, correspond to $z = \frac{x}{x_{\mathbb{P}}}$ where $x_{\mathbb{P}} = 0.05$, a typical diffractive value. x is therefore equivalent to x-Bjorken which is measured by the experiment. The symbols correspond to the following evolution equations:*
Circles: DGLAP. Filled triangles: GLR. Unfilled triangles: Modified GLR.
The bin widths of x and Q^2 were 0.001 and 4 GeV^2 respectively. $t \leq 0.2\ GeV^2$ and $0.01 \leq x_{\mathbb{P}} \leq 0.09$. The integrated luminosity was 100 pb^{-1}.