Charged particle multiplicity in diffractive deep inelastic scattering

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(Received 1 February 1999; published 21 June 1999)

The recent data from the H1 Collaboration on hadron multiplicity in diffractive DIS is studied in the framework of perturbative QCD as a function of invariant diffractive mass. The formulas obtained explain the observed excess of particle production in diffractive DIS relative to that in DIS and e^+e^- annihilation. It is shown that the results are sensitive to the quark-gluon structure of the Pomeron. Namely, the data are in favor of a superhard gluon distribution at the initial scale. [S0556-2821(99)02813-1]

PACS number(s): 13.60.Hb, 12.38.Bx, 12.40.Nn

I. INTRODUCTION

One of the most remarkable and intriguing discoveries in hadron physics in the last years was the observation of hard interactions (namely, partonic activity) in diffractive events by the UA8 Collaboration [1] at the CERN Collider. This discovery was inspired by a seminal paper by Ingelman and Schlein [2] in which such a possibility was foreseen as a consequence of the Pomeron having an internal structure and a quark-gluon content.

Experiments performed at the DESY ep collider HERA by the ZEUS [3] and H1 [4] Collaborations provided further elements to this view through the obtainment of deep inelastic electron-proton scattering (DIS) events accompanied by large rapidity gaps adjacent to the proton beam direction. The presence of rapidity gaps in such events is interpreted as indicative that the internal structure of a colorless object carrying the vaccum quantum numbers, namely the Pomeron, is being probed [3,4]. Further experimental evidence of hard diffraction has been reported by Collider Detector at Fermilab (CDF) and D0 Collaborations in terms of diffractive production of W's and dijets [5,6].

Taking together, this evidence seems to indicate that the Ingelman-Schlein (IS) picture [2] is right at least *qualitatively*. However, a serious problem arises when one checks this model quantitatively. For instance, the model predictions systematically overestimate the diffractive production rates of jets and W's [7]. There are reasons to believe that the discrepancy between predictions and data comes from the so-called Pomeron flux factor [8]. In fact, a recent analysis [9] has shown that the pomeron structure function extracted from HERA data by using the IS approach is strongly dependent on which expression is used for the flux factor.

Recently, new data from H1 Collaboration [10] on final hadronic states in diffractive deep inelastic process (DDIS) of the type

$$ep \to e' XY, \tag{1}$$

where X and Y are hadronic systems, have been presented. The system X and Y in Eq. (1) are separated by the largest rapidity gap. Y is the closest to the proton beam ($M_Y < 1.6$ GeV) and squared momentum transfer at the pY vertex t is limited to $|t| < 1\ \mathrm{GeV}^2$, while $\langle Q^2 \rangle$ is $21-27\ \mathrm{GeV}^2$ [10]. Both invariant masses M_X and M_Y are small compared to W, the center-of-mass energy of the $\gamma^* p$ system.

In particular, charged hadron multiplicity has been studied in Ref. [10] as a function of M_X in the center-of-mass system of X. The data obtained have been compared with the calculations of JETSET e^+e^- (which is known to reproduce well the e^+e^- data) and with the data on hadron multiplicities in deep inelastic scattering (DIS) [11]. The interesting observations presented in Ref. [10] are the following: (i) for $M_X > 10$ GeV, $\langle n \rangle^{\mathrm{DDIS}}(M_X, Q^2)$ is larger than charged hadron multiplicity in DIS $\langle n \rangle^{\mathrm{DIS}}(W, Q^2)$, at comparable values of $W = \langle M_X \rangle$; (ii) $\langle n \rangle^{\mathrm{DDIS}}(M_X, Q^2)$ is also larger than charged hadron multiplicity in e^+e^- annihilation $\langle n \rangle^{e^+e^-}(s)$, taken at $\sqrt{s} = \langle M_X \rangle$.

In the present paper we demonstrate that perturbative QCD is able to explain (qualitatively and quantitatively) the more rapid growth of hadron multiplicity in DDIS. So, no mechanisms besides gluon-quark jet emission with subsequent jet fragmentation into hadrons are needed. It is shown that the results on hadron multiplicity are very sensitive to the quark-gluon structure of the Pomeron. An advantage of the method developed here is that it does not depend on the Pomeron flux factor.

The paper is organized as follows. In Sec. II, we present the QCD formalism for the description of final hadron states in ordinary DIS. In Sec. III, we extend this formalism to diffractive DIS and apply it to describe the H1 data. Our main conclusions are summarized in Sec. IV.

II. HADRON MULTIPLICITIES IN HARD PROCESSES IN PERTURBATIVE QCD

For the time being, we cannot describe a transition of quark and gluons into hadrons in the framework of QCD. Nevertheless, perturbative QCD enables one to calculate an energy dependence of characteristics of final hadrons produced in hard process (e^+e^- annihilation into hadrons, DIS, Drell-Yan process, etc.). Mean hadron multiplicity $\langle n \rangle$ is one of the main features of final hadronic states. Hadron multiplicity in e^+e^- annihilation has been studied in a number of papers. The result can be expressed as (see, for instance, Ref. [12])

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$$\langle n\rangle^{e^+e^-}(s)=a(\ln s)^b\exp(c\sqrt{\ln s}),\tag{2}$$

where $\sqrt{s}$ is a total c.m.s. energy of colliding leptons. As one can see, $\langle n\rangle^{e^+e^-}(s)$ rises more rapidly than $\ln s$, although more slowly than any power of s. Expression (2) describes well the available data.

Hadron multiplicity in DIS was calculated first in the framework of perturbative QCD in Refs. [13] (see also Ref. [14]). It was shown that average multiplicity in lepton scattering off parton

$$eq(g)\to e'X,\tag{3}$$

$\langle n\rangle^{\rm DIS}_{q/g}(W,Q^2)$, is related to $\langle n\rangle^{e^+e^-}(s)$, the average multiplicity in e^+e^- annihilation, taken at $\sqrt{s}=W$ [up to small next leading order (NLO) corrections which descrease in W and Q^2] [13].

In a case when quark distribution dominates (say, at $x\simeq 1$), the relation between $\langle n\rangle^{\rm DIS}$ and $\langle n\rangle^{e^+e^-}$ is (up to small NLO corrections which decrease in W and Q^2) [13]

$$\langle\hat n\rangle^{\rm DIS}_{q}(W,Q^2)=\langle n\rangle^{e^+e^-}(W).\tag{4}$$

If we consider small x, we have to account for the gluon distribution and the result is of the following form [15]:

$$\langle\hat n\rangle^{\rm DIS}_{g}(W,Q^2)=\langle n\rangle^{e^+e^-}(W)\left[1+\frac{C_A}{2C_F}\varepsilon\left(1-\frac{3}{2}\varepsilon\right)\right],\tag{5}$$

where $C_A=N_c$, $C_F=(N_c^2-1)/2N_c$ and N_c is a number of colors.

The quantity ε is defined via gluon distribution (see Ref. [15] for details)

$$\varepsilon=\sqrt{\frac{\alpha_s(W^2)}{2\pi C_A}}\frac{\partial}{\partial\xi}\ln D^g(\xi,x),\tag{6}$$

ξ being the QCD-evolution parameter $\xi(W^2)=\int^{W^2}(dk^2/k^2)[\alpha_s(k^2)/2\pi]$. Let us notice that ε [Eq. (6)] does not depend on the type of the target, and ε is completely defined by the evolution of D^g in ξ.

Starting from the well-known expression for D^g_g at small x [16]

$$D^g_g(\xi,x)=\frac{1}{\ln(1/x)}v\,\mathrm{I}_1(2v)\exp(-d\xi),\tag{7}$$

where $v=\sqrt{4N_c\xi\ln(1/x)}$, $d=(1/6)(11N_c+2N_f/N_c^2)$, N_f is a number of flavors, we get

$$\varepsilon=\varepsilon(W^2,x)=\sqrt{\frac{\alpha_s(W^2)}{\pi}}\left[\sqrt{\frac{\ln(1/x)}{\xi(W^2)}}-\frac{d}{\sqrt{2N_c}}\right].\tag{8}$$

At $\ln(1/x)\gg 1$ [that is omitting the second term in the right-hand side of Eq. (8)] we come to the asymptotical expression for ε from Ref. [15].

Using Eqs. (4) and (5), we get in a general case,

$$\langle\hat n\rangle^{\rm DIS}(W,Q^2)=\langle n\rangle^{e^+e^-}(W)\left\{\Delta+\left[1+\frac{C_A}{2C_F}\varepsilon(W^2,x)\right.\right.$$
$$\left.\left.\times\left(1-\frac{3}{2}\varepsilon(W^2,x)\right)\right](1-\Delta)\right\},\tag{9}$$

where $\Delta/(1-\Delta)$ defines the quark/gluon ratio inside the nucleon. As was shown in Ref. [15], ε [Eq. (8)] is a leading correction to $\langle\hat n\rangle^{\rm DIS}$ which rises with the decreasing of x.

Everything mentioned above is related to the multiple production of the hadrons in DIS of lepton off the parton (3). It is a subprocess of the process of lepton deep inelastic scattering off the nucleon

$$ep\to e'X.\tag{10}$$

According to Refs. [14,17,18], the corresponding formula for mean hadron multiplicity in DIS is

$$\langle n\rangle^{\rm DIS}(W,Q^2)=\langle\hat n\rangle^{\rm DIS}(W_{\rm eff},Q^2)+n_0(M_0^2).\tag{11}$$

The quantitiy $\langle\hat n\rangle^{\rm DIS}$ has been defined above [see Eq. (9)]. It depends on the effective energy, $W_{\rm eff}$, available for hadron production in the parton subprocess (3):

$$W^2_{\rm eff}=kW^2.\tag{12}$$

The average multiplicity of nucleon remnant fragments n_0 is a function of its invariant mass $M_0^2=(1-z)(Q_0^2/z+M^2)$, where M is the nucleon mass.

The efficiency factor k in Eq. (12) was estimated in Ref. [14] to be $\langle k\rangle\simeq 0.15-0.20$ at present energies. That is why $\langle n\rangle^{\rm DIS}(W,Q^2)$ is less than $\langle n\rangle^{e^+e^-}(W)$ and the growth of $\langle n\rangle^{\rm DIS}(W,Q^2)$ in W at fixed Q^2 is delayed in comparison with that of $\langle n\rangle^{e^+e^-}(W)$.

III. AVERAGE HADRON MULTIPLICITY IN DIFFRACTIVE DIS

Hadronic system X in diffractive DIS (1) is produced as a result of the virtual photon-Pomeron interaction

$$e\mathbb{P}\to e'X.\tag{13}$$

The kinematical variables usually used to describe DDIS (in addition to W and Q^2) are

$$x_{\mathbb{P}}\simeq\frac{M_X^2+Q^2}{W^2+Q^2}\quad\text{and}\quad\beta\simeq\frac{Q^2}{M_X^2+Q^2}.\tag{14}$$

We start from the fact that pomeron has quark-gluon structure. This means that hadron production in process (13) is similar to that in parton subprocess of DIS (3).

Recently a factorization theorem for DDIS has been proven [19]. Structure functions of DDIS coincide with structure functions of DIS and have the same dependence on a factorization scale. As a result, distribution functions of

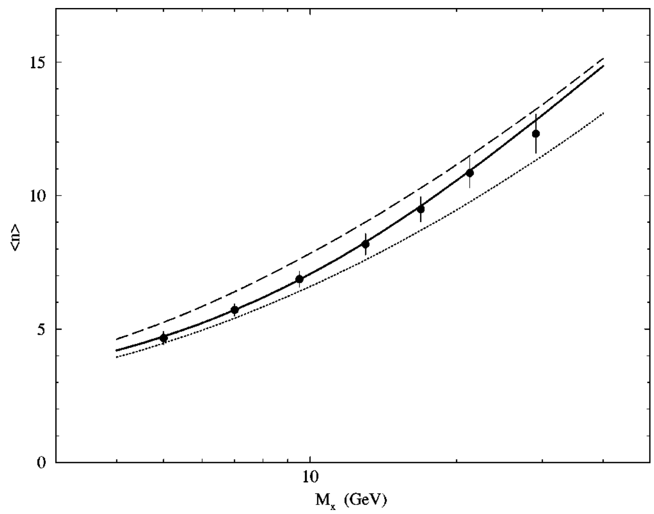

FIG. 1. Description of the average multiplicity of charged hadrons produced in diffractive DIS experiments. Data obtained by the H1 Collaboration [10]. The theoretical results are obtained from Eq. (15) with different assumptions for the quark/gluon content of the Pomeron: pure quark (dotted curve), pure gluon (dashed curve) and both components (solid curve).

quark and gluons inside the Pomeron $D_{\mathbb{P}}^{q(g)}$ must obey standard Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations at high Q^2 [20].

So, we can conclude that the hadron multiplicity of system X in DDIS $\langle n\rangle^{\rm DDIS}$ is given by expression (9), in which W is replaced by M_X, while x is replaced by β. Namely, we get

$$\langle n\rangle^{\rm DDIS}(M_X,Q^2)=\langle n\rangle^{e^+e^-}(M_X)\left\{\Delta_{\mathbb{P}}+\left[1+\frac{C_A}{2C_F}\varepsilon(M_X^2,\beta)\times\left(1-\frac{3}{2}\varepsilon(M_X^2,\beta)\right)\right](1-\Delta_{\mathbb{P}})\right\}. \quad (15)$$

Here $\varepsilon(M_X^2,\beta)$ is given by formula (8) and $\Delta_{\mathbb{P}}/(1-\Delta_{\mathbb{P}})$ defines the quark-gluon ratio inside the Pomeron. As both $D_{\mathbb{P}}^q$ and $D_{\mathbb{P}}^g$ obey DGLAP equations, the quantity $\varepsilon(M_X^2,\beta)$ and, consequently, hadronic multiplicity in DDIS are sensitive to the quark-gluon structure of the Pomeron at starting scale Q_0.

As follows from Eqs. (11) and (15),

$$\langle n\rangle^{\rm DDIS}(M_X,Q^2)>\langle n\rangle^{\rm DIS}(M_X,Q^2) \quad (16)$$

because $\langle n\rangle^{\rm DDIS}(M_X,Q^2)$ is defined by $\langle n\rangle^{e^+e^-}(M_X)$, while $\langle n\rangle^{\rm DIS}(M_X,Q^2)$ is expressed via $\langle n\rangle^{e^+e^-}(M_X^{\rm eff})$, the quantity $M_X^{\rm eff}$ being much smaller than M_X by factor k [see Eq. (12)].

For $M_X<29$ GeV we have $M_X^{\rm eff}<5-6$ GeV. It is known that in the region $W<5-6$ GeV function $\langle n\rangle^{e^+e^-}(W)$ rises logarithmically ($\sim\ln W$) that is slower than Eq. (2). This results in a more rapid growth of $\langle n\rangle^{\rm DDIS}(M_X,Q^2)$ in M_X in comparison with $\langle n\rangle^{\rm DIS}(M_X,Q^2)$.

We conclude from formula (15) that $\langle n\rangle^{\rm DDIS}(M_X,Q^2)$ should exceed $\langle n\rangle^{e^+e^-}(M_X)$. Moreover, the ratio $\langle n\rangle^{\rm DDIS}(M_X,Q^2)/\langle n\rangle^{e^+e^-}(M_X)$ has to grow in M_X at fixed Q^2 (which corresponds to the rise in $1/\beta$ at fixed Q^2). All said above is in good qualitative agreement with the data from the H1 Collaboration [10].

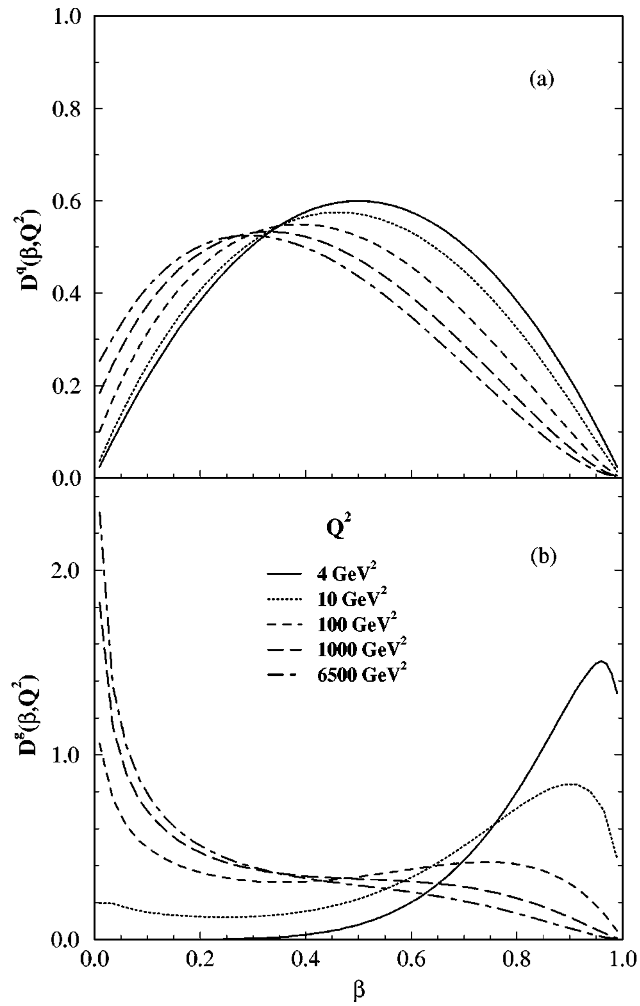

FIG. 2. Q^2 evolution of the quark singlet (a) and gluon (b) distributions obtained by the fitting procedure described in the text.

In Fig. 1 we show the result of the fits of the H1 data by using our formula (15) (solid curve). In order to obtain this result, we proceeded as follows. For the quantity $\Delta_{\mathbb{P}}$ which enters expression (15) we used

$$\Delta_{\mathbb{P}}(\beta,Q^2)=\frac{D_{\mathbb{P}}^q(\beta,Q^2)}{D_{\mathbb{P}}^g(\beta,Q^2)+D_{\mathbb{P}}^q(\beta,Q^2)}, \quad (17)$$

where $D_{\mathbb{P}}^g$ and $D_{\mathbb{P}}^q$ are, respectively, the gluon and the singlet quark distributions inside the Pomeron that, as mentioned above, obey DGLAP evolution equations [20]. For the distributions at the initial scale $Q_0^2=4$ GeV^2 the following forms were employed:

$$D_{\mathbb{P}}^q(\beta,Q_0^2)=a_1\beta(1-\beta),$$

$$D_{\mathbb{P}}^g(\beta,Q_0^2)=b_1\beta^{b_2}(1-\beta)^{b_3}. \quad (18)$$

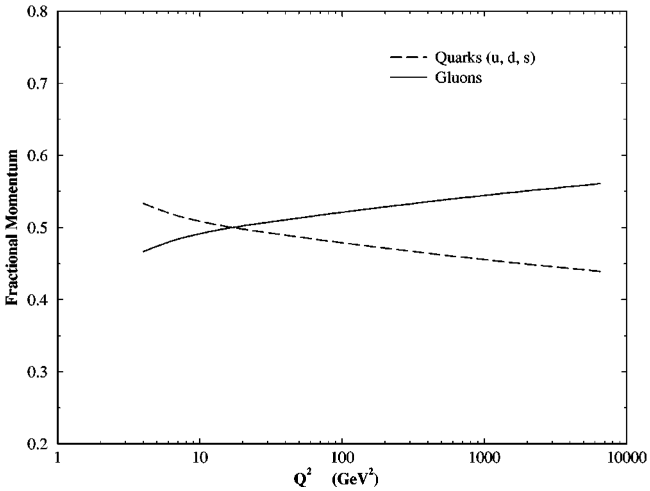

FIG. 3. Q^2 evolution of the fractions of the Pomeron momentum carried by quarks and gluons as predicted from the parametrization resulted from the fit to the H1 Collaboration data.

Thus, for the quark distribution we fixed an initial hard profile leaving free the normalization parameter, while for the gluon distribution we have left all parameters free without imposing any sum rule. In order to perform the fit, other elements are needed. In Eq. (15), for $\langle n\rangle^{e^+e^-}(M_X)$ we have used the parametrization

$$\langle n\rangle^{e^+e^-}(M_X)=2.392+0.024\ln\left(\frac{M_X^2}{M_0^2}\right)+0.913\ln^2\left(\frac{M_X^2}{M_0^2}\right) \tag{19}$$

with $M_0=1$ GeV, taken from Ref. [21]. In addition to that, the experimental data shown in Fig. 1 are given in terms of average values of M_X, β, and Q^2 that do not obey strictly the kinematical relation (14). In order to be faithful to data, we employed in our fit the parametrization

$$\langle\beta\rangle=\frac{a}{(1+b\langle M_X\rangle)^c}, \tag{20}$$

with $a=1.63$, $b=0.165\ \mathrm{GeV}^{-1}$, and $c=2.202$.

The dotted (dashed) line in Fig. 1 corresponds to a pure quark (gluon) content of the Pomeron. The solid line gives the fit of the H1 data with parameters $a_1=2.400$, $b_1=3.600$, $b_2=5.279$, and $b_3=0.204$ in Eqs. (18), which are evolved to the respective Q^2 value corresponding to each experimental point.

The initial distributions and their evolution with Q^2 are shown in Fig. 2. As can be seen, a superhard profile (peaked at $\beta\sim1$) was obtained for the gluon distribution at the initial scale, in qualitative agreement with H1 analysis [22].

The Q^2 evolution of the normalized fractions of the Pomeron momentum carried by quarks and gluons is presented in Fig. 3. It is shown that quarks are slightly predominant over gluons at the initial scale, but that this relation reverses as Q^2 evolves. In this case, our results do not follow those obtained by the H1 Collaboration since their analysis [10] favors a fit in which predominate gluons with $\geqslant 80\%$ of Pomeron momentum at the initial scale. It must be said, however, that the results of Fig. 3 are consistent with limits established in other experiments (see, for instance, Ref. [5]).

IV. CONCLUSION

We have presented in this paper a description of the hadron multiplicity obtained in diffractive DIS and recently reported by the H1 Collaboration [10]. This description was derived from a formalism previously developed for ordinary DIS within the framework of the perturbative QCD.

The formula obtained enables us to explain the observed excess of hadron multiplicity in diffractive DIS, $\langle n\rangle^{\mathrm{DDIS}}(M_X,Q^2)$, relative to those in DIS and e^+e^- annihilation taken at $W=\langle M_X\rangle$ and $\sqrt{s}=\langle M_X\rangle$, correspondingly. The more rapid growth of $\langle n\rangle^{\mathrm{DDIS}}(M_X,Q^2)$ is also understood.

It was shown (Fig. 1) that neither a pure quark nor a pure gluon content of the Pomeron satisfy the data, but that a mixing of both components in approximately equal shares is able to provide a good description of the experimental results. The Pomeron structure function that comes out from the present analysis consists of a hard distribution for the quark singlet and a superhard distribution for gluons at the initial scale of evolution, in agreement with what has been reported lately in the literature [22]. This result is remarkably good if one considers that it was obtained from a very small data set (only seven data points), covering a limited β range $(0.03<\beta<0.43)$ for an equally restricted Q^2 range $(22<Q^2<27\ \mathrm{GeV}^2)$.

Concluding, the most important result presented here is the theoretical framework summarized by Eq. (15), which has made it possible to explain anomalous H1 data on hadron multiplicity in DDIS. It also enabled us to extract information about the Pomeron structure function from such a limited data set, without the usual complications and ambiguities with flux factor normalization and $x_{\mathbb{P}}$ dependence.

This conclusion points out the need of more and more precise DDIS multiplicity data, taken at extended kinematical ranges. Such a possibility would much improve the analytical capacity of the scheme presented here.

ACKNOWLEDGMENTS

We would like to thank the Brazilian governmental agencies CNPq and FAPESP for financial support.

[1] UA8 Collaboration, R. Bonino *et al.*, Phys. Lett. B **211**, 233 (1988); UA8 Collaboration, A. Brandt *et al.*, *ibid.* **297**, 417 (1992).
[2] G. Ingelman and P.E. Schlein, Phys. Lett. **152B**, 256 (1985).
[3] ZEUS Collaboration, M. Derrick *et al.*, Phys. Lett. B **315**, 481 (1993); **332**, 228 (1994); **346**, 399 (1995); Z. Phys. C **68**, 569 (1995).
[4] H1 Collaboration, T. Ahmed *et al.*, Nucl. Phys. **B429**, 477 (1994); Phys. Lett. B **345**, 3 (1995); **348**, 681 (1995).
[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **78**, 2698 (1997); **79**, 2636 (1997).
[6] D0 Collaboration, S. Abachi *et al.*, paper presented at the *28th International Conference on High Energy Physics (ICHEP 96)*, Warsaw, Poland, 1996, edited by Z. Ajduk and A.K. Wroblewski (World Scientific, Singapore, 1997).
[7] L. Alvero *et al.*, Phys. Rev. D **59**, 074022 (1999); R.J.M. Covolan and M.S. Soares, Phys. Rev. D (to be published).
[8] K. Goulianos, Phys. Lett. B **358**, 379 (1995).
[9] R.J.M. Covolan and M.S. Soares, Phys. Rev. D **57**, 180 (1998).
[10] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **5**, 439 (1998).
[11] EMC Collaboration, M. Arneodo *et al.*, Nucl. Phys. **B258**, 249 (1985).
[12] B.R. Webber, Phys. Lett. **143B**, 501 (1984).
[13] G.Sh. Dzhaparidze, A.V. Kisselev, and V.A. Petrov, Yad. Fiz. **35**, 1586 (1982) [Sov. J. Nucl. Phys. **35**, 927 (1982)]; A. Bassetto, Nucl. Phys. **B202**, 493 (1982).
[14] A.V. Kisselev and V.A. Petrov, Part. Nuclei **19**, 21 (1988).
[15] A.V. Kisselev and V.A. Petrov, Phys. Lett. B **214**, 434 (1989).
[16] Yu.L. Dokshitzer *et al.*, *in Perturbative Quantum Chromodynamics*, edited by M. Jacob (North-Holland, Amsterdam, 1982), p. 431.
[17] V.A. Petrov, A.V. Kisselev, and O.P. Yushchenko, Phys. Lett. B **193**, 357 (1987).
[18] A.V. Kisselev and V.A. Petrov, Phys. Lett. **131B**, 468 (1989).
[19] J. C. Collins, Phys. Rev. D **57**, 3051 (1998).
[20] V.N. Gribov and L.V. Lipatov, Yad. Fiz. **15**, 781 (1972) [Sov. J. Nucl. Phys. **15**, 438 (1972)]; *ibid.* **15**, 1218 (1972) [*ibid.* **15**, 675 (1972)]; G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977); Yu.L. Dokshitzer, Zh. Eksp. Teor. Fiz. **73**, 1216 (1977) [Sov. Phys. JETP **46**, 641 (1977)].
[21] M. Batista and R.J.M. Covolan, Phys. Rev. D **59**, 054006 (1999).
[22] H1 Collaboration, C. Adloff *et al.*, Z. Phys. C **76**, 613 (1997).