Nonlinear Pomeron trajectory in diffractive deep inelastic scattering

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Recent experimental data on diffractive deep inelastic scattering collected by the H1 and ZEUS Collaborations at DESY HERA are analyzed in a model with a nonlinear trajectory in the Pomeron flux. The t dependence of the diffractive structure function $F_2^{D(4)}$ is predicted. The normalization of the Pomeron flux and the (weak) Q^2 dependence of the Pomeron structure function are revised as well. [S0556-2821(96)01423-3]

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I. INTRODUCTION

Diffractive deep inelastic scattering (DIS), or ''hard diffraction,'' is a subclass of semi-inclusive deep inelastic reactions in which a virtual point-like particle (quark or lepton) is assumed to interact directly with a colorless object emitted by the proton target. This may happen in a special kinematical configuration when the hit proton continues its motion nearly in the forward direction.

There are several reasons why this class of reactions is receiving so much attention. The first and most obvious one comes from the prospect to study the internal structure of the Pomeron, a hypothetical quasiparticle with the quantum numbers of vacuum, responsible for diffraction in the Regge pole model. Although the composite nature of the Pomeron, within the context of the quark model and QCD, was never a question for the theorists, the possibility of its experimental verification in deep inelastic scattering was first formulated in Ref. [1]. In subsequent experiments of the UA8 Collaboration [2], two-jet events were reported as an evidence of the partonic structure of the Pomeron.

The study of the so-called ''large rapidity gap'' events at the DESY ep collider HERA initiated by the ZEUS Collaboration [3], revitalized the subject. HERA produced a large number of high-precision data in a wide kinematical range of x and Q^2, published recently by the H1 [4] and ZEUS [5] Collaborations. A new and important development in the subject is the experimental study of the t dependence of the cross sections, ignored until recently.

Theoretical studies of the diffractive deep inelastic scattering (hard diffraction) were pioneered by the papers [1,6,7], long before the HERA experimentations. Now, there is a large literature (partially listed in Refs. [8–15], we apologize to those not included because of the limited scope of the present paper) dealing with various aspects of the phenomenon. In our opinion, the present state of the subject can be summarized as follows.

There is nothing surprising in the very existence of the large rapidity gap events (occurring, e.g., also in the $p\bar{p}$ diffraction dissociation) provided diffraction, the Regge pole model, and properties of the S matrix do not change essentially when one of the external particles goes off shell. The last assumption is the most delicate one in the whole subject, and we shall come back to it.

The next question is whether the appearance of a rapidity gap, within which secondary particles are not produced, is a manifestation of diffraction, and, if so, is it a Pomeron exchange, or can it be simulated by an alternative mechanism. The answer to the first is ''yes,'' to the extent other features of diffraction, namely, typical ξ (or x_{IP}) and t dependence, will be confirmed.

The ξ dependence has been recently measured and found to be $\approx \xi^{-a}$ with the values $a = 1.30 \pm 0.08(\mathrm{stat})^{+0.08}_{-0.14}(\mathrm{syst})$ as measured by ZEUS [5] and $a = 1.19 \pm 0.06(\mathrm{stat}) \pm 0.07(\mathrm{syst})$ by H1 [4]. These two values, although obtained with different selection criteria, are compatible and both agree with the Pomeron intercept [16] most reliably extracted from the p-p and p-$\bar{p}$ total cross section. The t dependence is now being measured and we discuss it below.

We assume that, similar to hadronic reactions, diffractive DIS is also mediated by a Pomeron exchange. Alternative approaches to this process have been discussed in [10,11]. A factorizable vacuum Regge pole exchange with the trajectory whose intercept is slightly beyond one, $\alpha(0) = 1 + \epsilon$, is known to be the adequate mechanism of diffraction, at least in hadronic reactions. Whether and how is the formalism affected by off mass shell effects is an open question. In any case the use of the Pomeron exchange is more justified in diffractive DIS, where at least the Pomeron interaction is directly related to hadronic diffraction, than generally in a

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(small-x) DIS, related to the absorptive part of the elastic γ^*-p scattering only for $t=0$.

The large Q^2 flow along the photon line was an argument for many authors to use perturbative QCD calculations for a single- [10] or two-gluon (Pomeron) [12] exchange in diffractive DIS. In our opinion, the use of perturbative QCD may be justified only in resolving the Pomeron structure (QCD evaluation of the photon Pomeron vertex), while the exchanged object, the Pomeron propagator, is essentially nonperturbative and it is the same, whatever is the photon virtuality. A more detailed discussion concerning the uniqueness of the Pomeron in elastic and deep inelastic scattering may be found in Ref. [17].

The above construction relies very much on the hypotheses of factorization of the diffractive structure function $F_2^{D(4)}$ into a product of the Pomeron flux and the Pomeron structure function. Whereas small deviations from factorization, e.g., due to multi-Pomeron exchanges, initial and final state interactions, etc., are admissible, other Regge contributions, e.g., the f exchange, can produce larger breaking effects and certainly should be accounted for in future calculations. At the moment, according to the published measurements at HERA [4,5], factorization is confirmed at the present level of accuracy.

With the present paper, we try to contribute by one more step in the clarification of the remaining uncertainties. First of all in Sec. II we introduce notations and define the kinematics. Next in Sec. III we discuss the Pomeron flux and its (re)normalization. The Pomeron structure function and the comparison with the experimental data are developed in Sec. IV while Sec. V is devoted to a study of the t dependence of the distribution function. We use the earlier experience based on the description of hadron diffraction with a nonlinear Pomeron trajectory [19] to predict the t dependence of the diffractive DIS.

II. NOTATION AND KINEMATICS

The notation and kinematics for the process

$$e^-(k)+p(p)\rightarrow e^-(k')+p(p')+X(p_X) \tag{1}$$

are standard. The four-momenta of the virtual photon and of the exchanged Reggeon are $q=k-k'$ and $r=p\text{-}p'$, respectively. Besides the usual DIS variables $Q^2=-q^2$, $x=Q^2/(2p\cdot q)$, and $W^2=(p+q)^2$, the new variables

$$\beta=\frac{Q^2}{2r\cdot q}, \quad \xi=\frac{r\cdot q}{p\cdot q}=\frac{x}{\beta} \tag{2}$$

are introduced. Sometimes, ξ is also called $x_{\rm IP}$.

Let M_X be the invariant mass of the hadronic system X, $p_X^2=M_X^2$, then the four-momentum transfer squared, $t=r^2$, ranges between the extreme limits

$$t_{\mp}=\left(\frac{M_X^2+Q^2}{2W}\right)^2-\left\{\left[\left(\frac{W^2-Q^2-m_p^2}{2W}\right)^2+Q^2\right]^{1/2}\mp\left[\left(\frac{W^2+M_X^2-m_p^2}{2W}\right)^2-M_X^2\right]^{1/2}\right\}^2 \tag{3}$$

or

$$t_-\sim -m_p^2x^2\left(1+\frac{M_X^2}{Q^2}\right)^2\sim -m_p^2\xi^2,$$

while $t_+\sim -W^2$ is a formal limit since $|t|$ is less than ~ 7 GeV^2 for the measurement in Ref. [4]. Experimentally, the t distribution has never been measured until recently because of the existing difficulties in identifying the proton hit by the photon but continuing its motion in nearly forward direction.

On the other hand, it is well known from the hadronic physics that diffraction is typical of the domain of about $|t|\leqslant 2$ GeV^2. In this region, the elastic differential cross section is known to decrease almost exponentially up to about $|t|\simeq 1$ GeV^2, followed by a dip-bump structure between 1 and 2 GeV^2. The latter is an important feature of high energy diffraction. The deviation from the exponential behavior of the cone may be taken into account by a nonlinear trajectory. We already discussed [18] the relevance of a nonlinear trajectory that interpolates between ''soft'' and ''hard'' scattering. A simple representative example is [19]

$$\alpha(t)=\alpha_0+\alpha_1 t-\alpha_2\ln(1-\alpha_3 t), \tag{4}$$

where $\alpha_0=1+\epsilon$ and $\alpha_i(i=1,2,3)$ are parameters. There are theoretical reasons [20] to consider logarithmic trajectories that, for large $-t$, are compatible with fixed angle scaling behavior of the amplitude. The square-root parametrization, adopted in [18], described the transition to the Orear (small-t) regime of the amplitude but, for a detailed study of the t dependence, the logarithmic form seems preferable as compared to the previous one.

The diffractive structure function is defined from the cross section as in [9] and the factorization hypothesis can be written as

$$F_2^{D(4)}(x,Q^2,t,\xi)=F_{{\rm IP}/p}(\xi,t)G_{q/{\rm IP}}(\beta,Q^2). \tag{5}$$

$F_{{\rm IP}/p}(\xi,t)$ and $G_{q/{\rm IP}}(\beta,Q^2)$ are, respectively, the Pomeron flux and the Pomeron structure function, to be introduced in the next two sections. We quote also the upper and lower kinematical limits for ξ typical of the H1 and ZEUS data:

	H1	ZEUS
ξ_H	0.05	0.01
ξ_L	3×10^{-4}	6.3×10^{-4}

III. THE POMERON FLUX AND ITS (RE)NORMALIZATION

As in Ref. [18], we fix the form of the scattering amplitude following the duality prescription. In dual models the dependence on the Mandelstam variable t enters the amplitude only through the trajectory $\alpha(t)$. Hence, in the Regge limit, $s\rightarrow\infty$ at fixed t,

$$A(s,t)=\exp[B(s)\alpha(t)], \tag{6}$$

where $B(s)=B_{\rm el}+\ln(s/s_0)-i\pi/2$.

The interest for a possible flattening of the Pomeron trajectory increased in view of the recent experimental result of the UA8 Collaboration [21]. In order to make clear the effect of a nonlinear $\alpha(t)$ we will consider Eq. (4) in the two limiting cases

$$\text{(a)} \quad \alpha_2=0: \ \alpha(t)=\alpha(0)+\alpha' t, \tag{7}$$

$$\text{(b)} \ \alpha_1=0, \ \alpha_2=\alpha_3: \ \alpha(t)=\alpha(0)-\gamma\ln(1-\gamma t). \tag{8}$$

The first instance has been studied in Ref. [18] for different choices of $\alpha(0)$ and $\alpha'=0.25$. In case (b) we will choose $\gamma=0.5$ in order to reproduce the same slope near $t=0$ and to deal with a trajectory close to the optimal solution of Ref. [19].

The constant term in $B(s)$, $B_{\rm el}$, has been determined from a fit to the elastic p-p differential cross section at the CERN Intersecting Storage Rings (ISR) [22]. For the Pomeron flux,

$$F_{\,\mathrm{IP}/p}=C\exp[2(B-\ln\xi)\alpha(t)]\cdot\xi, \tag{9}$$

we get

$$B=B_{\rm diff}=B_{\rm el}/2\simeq 7.0.$$

The main hypothesis here is that only the Pomeron trajectory contributes to the single diffractive cross section, a condition supported from the experimental evidence for factorization. Since the trajectory (8) is an effective one, the best determination of $\alpha(0)$ comes from the overall Regge fit of total cross sections in Ref. [16]

$$\alpha(0)\simeq 1.08.$$

We will use in the following this value that differs slightly from the CDF intercept $\alpha(0)=1.112\pm0.013$ [23] obtained from total cross section data, but provides a sensible determination of the constant in front of the flux (9).

From Ref. [16] we get the Pomeron contribution to p-p total cross section and find

$$c\equiv C\exp[2B\alpha(0)]=\frac{21.7}{16\pi}mb=1.1087\ \mathrm{GeV}^{-2}. \tag{10}$$

From the same fit we deduce that the contribution to the cross section of nonasymptotic Regge terms $(\rho,f,\ldots)$ is rather small at HERA, approximately 8% at the lowest W values. As seen in Fig. 1, there is a marked difference in the t dependence of the Pomeron flux derived from a logarithmic trajectory, curve (1), or a linear one, curve (2). Curves (3) [8] and (4) [6] refer to models for the Pomeron flux approaching the limiting cases represented by Eqs. (7) and (8).

The integrated Pomeron flux for the nonlinear trajectory (8) is

$$\Phi(\xi)\equiv\int_{t_+}^{t_-}F_{\,\mathrm{IP}/p}(\xi,t)dt$$
$$=\frac{c}{\gamma}\frac{(1-\gamma t_-)^{-b(\xi)}-(1-\gamma t_+)^{-b(\xi)}}{b(\xi)}\xi^{1-2\alpha(0)}$$
$$\simeq\frac{c}{\gamma b(\xi)}\xi^{1-2\alpha(0)}, \tag{11}$$

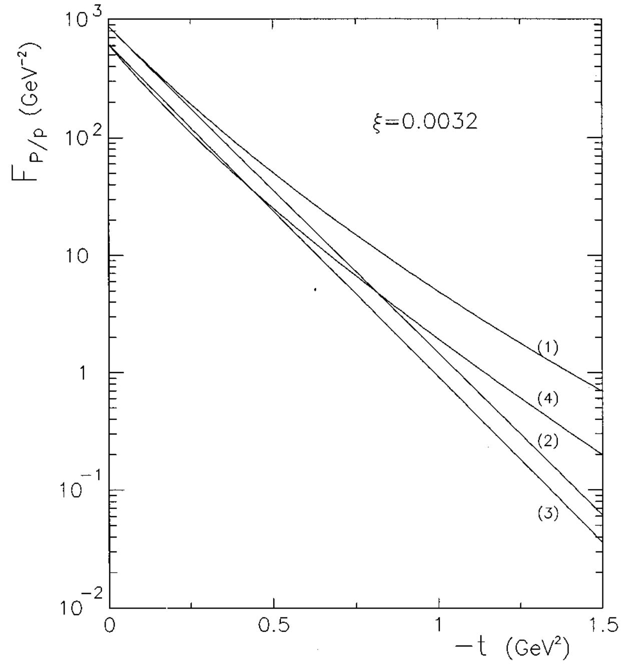

FIG. 1. The Pomeron flux $F_{\,\mathrm{IP}/p}(\xi,t)$ vs $-t$ for $\xi=0.0032$ with the logarithmic trajectory (1) or the linear one (2) discussed in the text. For comparison the Pomeron fluxes (3) of Ref. [8] and (4) of Ref. [6] are also drawn.

where

$$b(\xi)=2\gamma(B-\ln\xi)-1.$$

The approximation in Eq. (11) is reasonable since $t_-\propto-\xi^2$ and $|t_+|$ is rather large, $|t_+|\simeq 7\ \mathrm{GeV}^2$ for the measurement described in Ref. [4].

Now, the ξ,t dependence of the diffractive structure function is completely fixed within the model. In order to set the normalization and to make a comparison with the experimental data we need the Pomeron structure function.

Renormalization of the Pomeron flux [14] affects only the determination of the Pomeron structure function. If we require that no more than one Pomeron should be exchanged in one diffractive proton interaction, then a bound must be imposed on the integral

$$\int_{\xi_L}^{\xi_H}\Phi(\xi)d\xi\simeq\frac{c}{2\gamma^2}e^{-f(1)}\{\mathrm{Ei}[f(\xi_L)]-\mathrm{Ei}[f(\xi_H)]\}, \tag{12}$$

where

$$f(\xi)=2[\alpha(0)-1]\left(B-\frac{1}{2\gamma}-\ln\xi\right)$$

and ξ_H, ξ_L are the upper and lower kinematical limits for ξ specified in Sec. II. In Eq. (12), $\mathrm{Ei}(z)$ is the exponential integral [24], and the numerical values of the integrated flux are 1.34 for ZEUS [5] and 2.42 for H1 [4]. For a linear trajectory (7) these values are somewhat smaller: 1.23 and 2.23, respectively. Considering the unitarization procedure explained in Ref. [14], flux renormalization should be applied also to some (Q^2,β) bins of the ZEUS data, in particular for small Q^2 and large β. Since corrections remain within experimental errors we do not scale down the integrated flux.

IV. THE POMERON STRUCTURE FUNCTION AND COMPARISON WITH EXPERIMENTAL DATA

As in our previous paper [18], we consider a Pomeron composed mainly of gluons. This point of view reflects the structure of the Balitskii-Fadin-Kuraev-Lipatov (BFKL) Pomeron [25] that, at least for large momentum transfers, relies on a sound basis. Nonperturbative effects will represent a new contribution to the aforesaid picture but should not change the Pomeron content. On its gluon content both theoretical [15] and experimental [26] constraints exist. Experimental data indicate that a large fraction of the Pomeron momentum, up to 80%, can be carried by hard gluons [26] and that the Pomeron structure function is approximately independent of Q^2 [4,5].

Since only quarks interact with the photon, quarks must be present in the input distribution with a fraction of the Pomeron momentum larger than 20%. In Ref. [18] we noticed that, at large β, to the assumed gluon distribution

$$\beta G(\beta,Q^2)=a(Q^2)(1-\beta), \tag{13}$$

one must add the $q\overline{q}$ sea contribution. Quark loops and the mesonic trajectories, included in the effective trajectory (8), will give rise to a quark distribution

$$\beta q_i(\beta,Q^2)=d(Q^2)\beta(1-\beta) \tag{14}$$

for the quark i, whose form we borrow from Ref. [6]. Both distributions contribute at the starting scale $Q_0^2=5\ \text{GeV}^2$ and, due to the presence of quarks, the previous estimate of the evolution [18] does not hold now.

We can keep, however, the calculation simple and transparent if we neglect gluon recombination effects [9] and limit ourselves to the low-Q^2 region, $Q^2\leqslant 40\ \text{GeV}^2$. This condition will not destroy the predictive power of the result since ''there is no evidence for any substantial Q^2 dependence of $\widetilde{F}_2^D$'' [4], a function proportional to the Pomeron structure function.

We use a recursive method for solving the massless inhomogeneous Altarelli-Parisi equations. This method is based on the power expansion of the solution in the parameter s:

$$s=\ln\left(\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right)$$

and, since it has been explained at full length in Appendix A of Ref. [27], we will not repeat the details here. We choose $Q_0^2=5\ \text{GeV}^2$, $\Lambda=0.2$ GeV and, taking into account gluon to quark conversion, the result at small s is

$$\begin{aligned}\beta q_i(\beta,Q^2)\simeq\, & d\beta(1-\beta)(1-s)\\ & +\varepsilon s\left\{\frac{4}{3}d\beta(1-\beta)\left[1+\ln\left(\frac{(1-\beta)^2}{\beta}\right)\right]\right.\\ & \left.+\frac{1}{2}a\left(\frac{2}{3}-\beta^2+\frac{\beta^3}{3}+\beta\ln\beta\right)\right\}\end{aligned} \tag{15}$$

with

$$a=a(Q_0^2),\quad d=d(Q_0^2)$$

and

$$\varepsilon=\frac{6}{33-2f},$$

where f is the number of quark flavors.

With three flavors, $f=3$, the Pomeron structure function is

$$G_{q/\mathrm{IP}}(\beta,Q^2)=\frac{4}{3}\beta q_i(\beta,Q^2). \tag{16}$$

Parameters a and d are not independent since we impose the momentum sum rule in the form

$$\int_0^1 d\beta\ \beta\left[\sum_i q_i(\beta,Q_0^2)+G(\beta,Q_0^2)\right]=1,$$

obtaining the constraint

$$d=\frac{1}{2}(2-a). \tag{17}$$

While a proof of the validity of this sum rule for the Pomeron is lacking [28], its applicability appears reasonable once a model for the Pomeron in terms of its constituents is assumed [8,9,14]. In fact, for the Pomeron structure function as defined in [1], motivations for the saturation of the sum rule have been given in [8] and the ''discrepancy factor'' is close to unity also for deep inelastic diffraction [14] if the Pomeron flux is properly normalized. Moreover, the analogy with the photon [6] cannot be pushed too far since the Pomeron, at difference with the photon, Reggeizes and its composite structure can be described in QCD [25].

Insisting on the particle nature of the Pomeron we can evaluate the total momentum carried by quarks and antiquarks

$$M(Q^2)=6\int_0^1\beta q_i(\beta,Q^2)d\beta=d+\frac{s}{9}\left(a-\frac{77}{9}d\right)$$

and, taking into account the relation (17), we find that the Q^2 dependence disappears for $a=154/95$.

This value is not far from the one obtained in fitting to the data,

$$a=1.458,$$

that gives a weak dependence on Q^2 with $dM(Q^2)/dQ^2<0$. The relative contribution of quarks to the Pomeron momentum is near 0.25 in the range of Q^2 where the recursive method applies. The presence of quarks at every Q^2 scale simulates a quarkball [15].

A plot of all ZEUS data for $F_2^{D(3)}$ [5] for different β values, regardless of their Q^2 values, as in Figs. 2(a)–2(c), shows that the Q^2 dependence is indeed weak. The large errors permit only to say that our model is compatible with

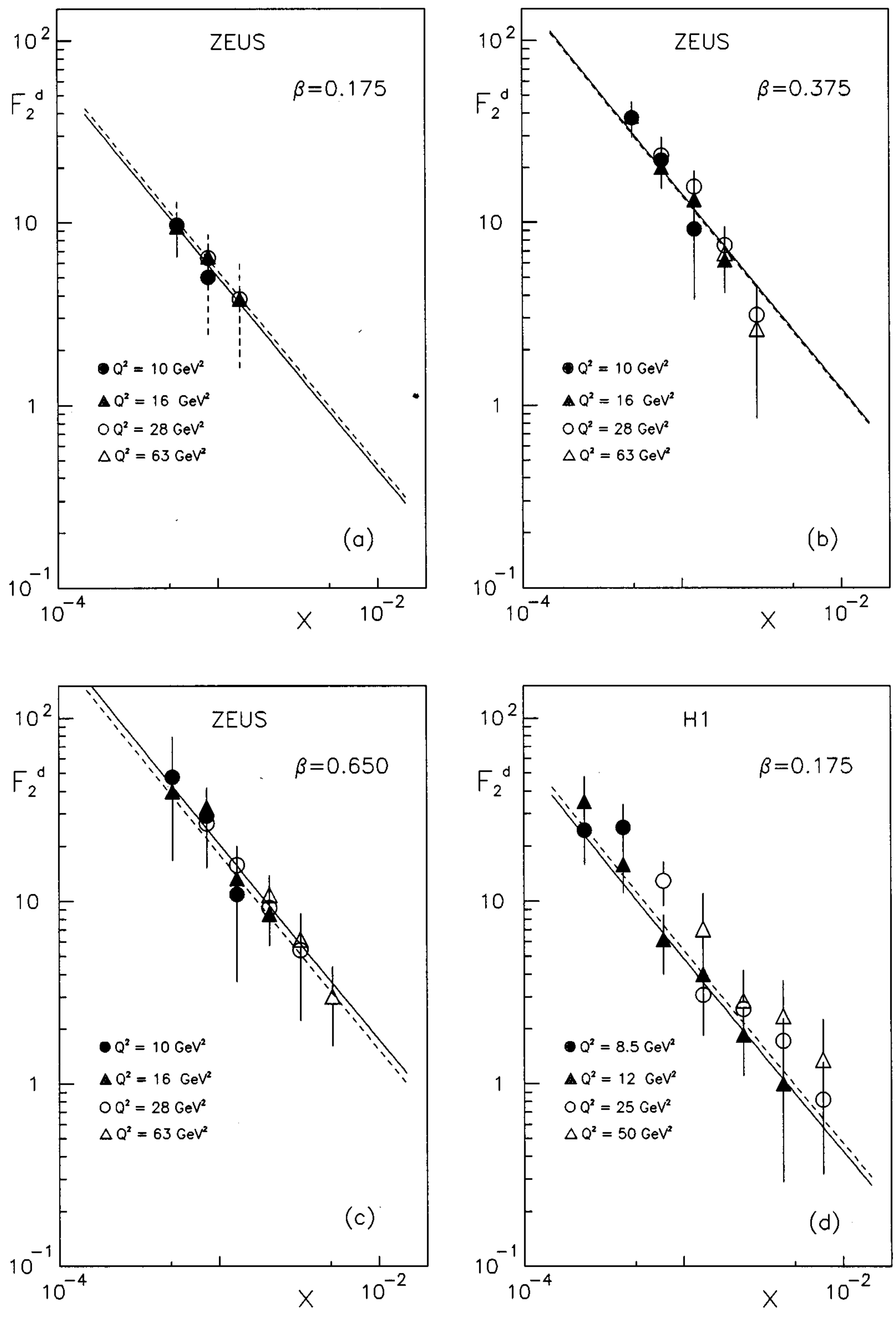

FIG. 2. The diffractive structure function $F_2^{D(3)}(\beta,Q^2,x)$ vs x, for different values of β and Q^2 (a), (b), and (c) compared with the ZEUS data [5], and (d) with the H1 data [4]. $F_2^{D(3)}$ has been evolved at $Q^2=16$ GeV^2 (continuous line) and $Q^2=28$ GeV^2 (dashed line) for the ZEUS data. For the H1 data, $Q^2=12$ GeV^2 (continuous line) and $Q^2=25$ GeV^2 (dashed line).

data. Continuous and dashed lines are the result of the evolution at $Q^2=16$ and 28 GeV^2, respectively, with the nonlinear trajectory (8) in the flux. No visible change is noticed if the calculation is repeated with the linear trajectory (7).

In comparison, the H1 data, presented in Fig. 2(d) for one β value shows a larger spread in Q^2. In this case the selected values of Q^2 for the fit are $Q^2=12$ GeV^2 (continuous curve) and 25 GeV^2 (dashed curve).

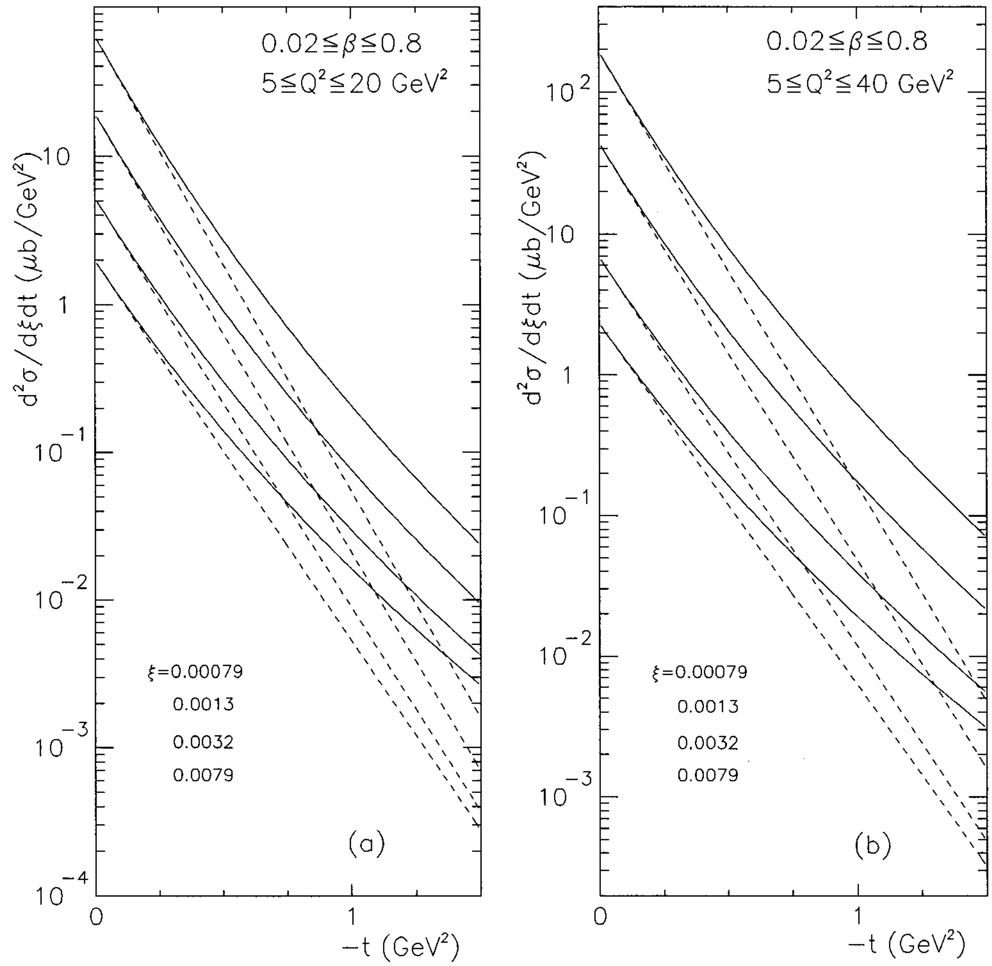

FIG. 3. The diffractive cross section $d^2\sigma/d\xi dt$ predicted from the model, vs $-t$ for different ξ values. The order of the ξ values is respected in the curves. Two different integration regions for Q^2 are considered: (a) 5 $\mathrm{GeV}^2 \leqslant Q^2 \leqslant 20$ GeV^2 and (b) 5 $\mathrm{GeV}^2 \leqslant Q^2 \leqslant 40$ GeV^2. Predictions from the logarithmic trajectory (full lines) and from the linear one (dashed lines) are shown.

V. PREDICTIONS AND CONCLUSIONS

In order to get a significant picture of the predictions from the model, we integrate over β and Q^2 the differential cross section expressed as

$$\frac{d^4\sigma^{\rm diff}}{d\beta dQ^2 d\xi dt} = \frac{2\pi\alpha^2}{\beta Q^4}[1+(1-y)^2]F_{\,\mathrm{IP}/p}(\xi,t)G_{q/\,\mathrm{IP}}(\beta,Q^2), \tag{18}$$

where

$$y \simeq \frac{Q^2}{s\beta\xi}$$

and $s=(296\ \mathrm{GeV})^2$. The β range of integration is restricted to the interval

$$0.02 \leqslant \beta \leqslant 0.8$$

and the upper limit avoids the region near $\beta=1$ where theoretical and experimental uncertainties are larger.

The Q^2 integration has been performed for two different intervals, both comprised in the region less sensitive to theoretical approximations. The starting scale $Q^2=5$ GeV^2 for evolution is the lower limit in both cases and the $d^2\sigma/d\xi dt$ results are displayed in Figs. 3(a) and 3(b). Predictions based on the logarithmic trajectory (8), continuous lines in Fig. 3, are clearly distinguishable from the ones obtained with the linear trajectory (7), dashed lines. Future experimental data, even at moderate $|t|$ values, will be able to decide between the two possibilities.

The t dependence shown in Figs. 1, 3(a), and 3(b) has a nature typically diffractive, i.e., it is strongly peaked in the forward direction. At present, the (nearly) exponential decrease of the differential cross section $d^2\sigma/d\xi dt$ to large extent has been fed in by the choice of the residue and form of the Pomeron trajectory. Nevertheless, this result is far from being trivial since in the formalism under consideration, the t dependence is correlated with other variables and ultimately the choice of different inputs (Pomeron trajectories) will be tested experimentally.

Data on the t dependence of the diffractive structure function have been discussed recently by two experimental groups: ZEUS [29] and UA8 [21]. We just notice that the UA8 results show the same trend in the behavior of the differential cross section that derives from the use of the logarithmic trajectory (8). The results of the measurement of the t dependence at HERA are preliminary and still not complete.

The knowledge of the t distribution will settle important questions. For example, the photon-Pomeron vertex may be also t dependent and it may bias the discussed behavior of the structure function.

Another prominent feature in the t dependence of diffraction, well-known in elastic hadron scattering, is the apperance of the diffraction minimum. The expected effect should be visible ''by eye'' because of its unmistakable structure, but the energy (here, W) and t values where the minimum should appear are near the kinematical boundary of the relevant experiments on deep inelastic diffractive scattering. For the above (kinematical) reason it has not yet been seen even in hadronic diffractive dissociation. Our model, as well as others, do not contain this structure. Its experimental observation, however, would resolve all doubts concerning the diffractive nature of the ''large rapidity gap events'' and related phenomena.

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