

## Rapidity Gaps in Deep Inelastic Scattering \*

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### Abstract

A simple semiquantitative picture of diffractive electroproduction is described. Although the diffractive component of  $F_2$  is approximately independent of  $Q^2$  and  $W^2$ , this mechanism is “soft,” i.e. it depends upon large-distance physics and is not readily describable within perturbative QCD.

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# 1 Introduction

The subject of this talk has become of considerable current interest, as evidenced by the other presentations at this meeting [1, 2, 3] on both experimental and theoretical developments. The main thrust of this one is to argue that, despite a growing tendency for experimentalists and theorists to say otherwise, the presence of a diffractive contribution which at large  $Q^2$  and small  $x$  “scales”, i.e. comprises a finite fraction (of order 5 to 10 percent) of all events, does not imply that the mechanism which creates this class of events is pointlike. Furthermore, a long standing mechanism [4] for creating the observed nondiffractive final-state properties (the so-called “aligned-jet” mechanism) appears quite sufficient to account for the bulk of the experimental evidence on diffractive final states.

It is especially appropriate to discuss this at this meeting, the 50th anniversary celebration of ITEP, because for me its origins go back to what I learned in my visits here in the early 1970s. Foremost was the very early observation by Ioffe [5] that, at small  $x$  and at large  $Q^2$ , large longitudinal distances  $z$  are important in the spacetime structure of the forward virtual-photon-proton Compton amplitude, the absorptive part of which determines the deep-inelastic structure functions. In the target-proton rest frame the estimate is roughly

$$z = \frac{1}{M_p x} \approx \frac{2\nu}{Q^2}. \quad (1)$$

Later, Gribov [6] used this observation to argue that generalized vector-meson dominance could provide an estimate of the behavior of the structure function in the limit of very small  $x$  and very large target (e.g. a nucleus). He used a most straightforward line of reasoning, which however led to a paradox, indeed a disaster, because the resultant structure function did not even approximately scale—it was too big at large  $Q^2$  by a full power of  $Q^2$ . It is this paradox and its resolution which is

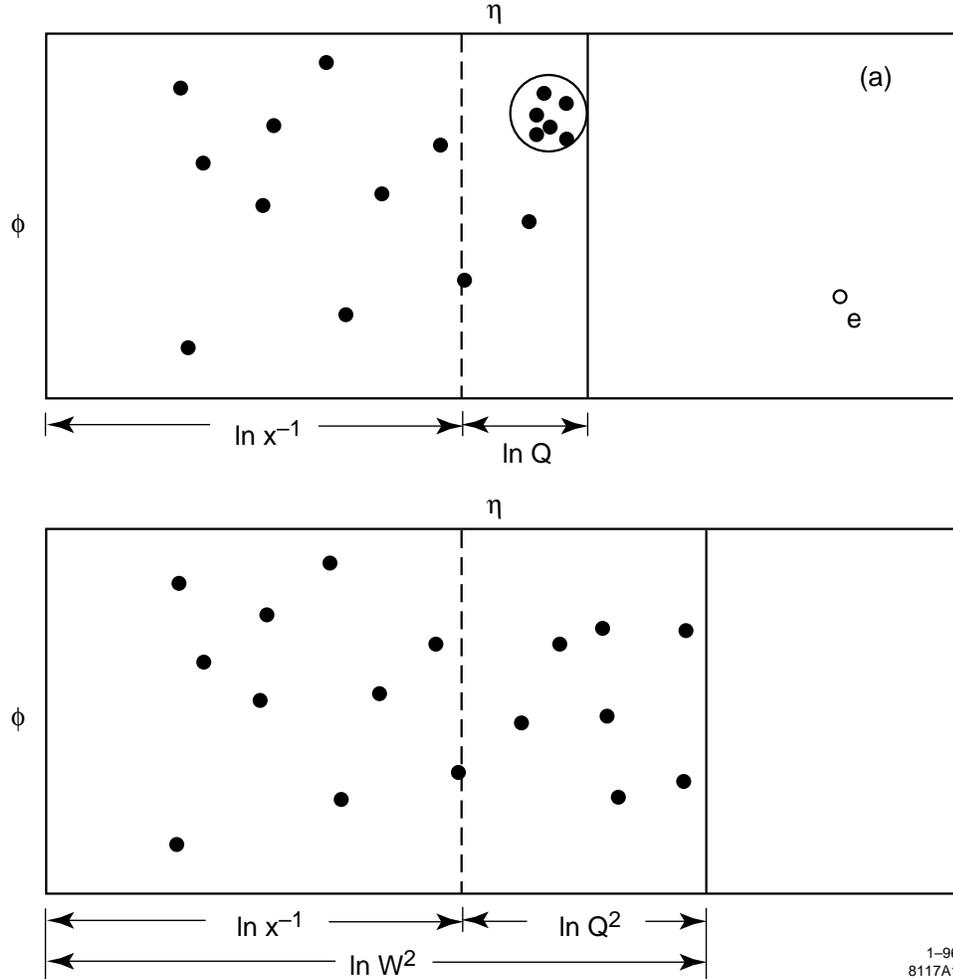
the centerpiece of the discussion to follow.

## 2 Basic physics of $F_2(x, Q^2)$ at small $x$

The familiar parton picture of deep-inelastic scattering is easy to apply at small  $x$ , especially in a typical HERA laboratory frame of reference. A right-moving electron “sees” a left-moving wee parton in the extreme-relativistic left-moving proton, and Coulomb-scatters from it with momentum transfer  $Q$ . The lego-plot picture of the final-state particles is sketched in Fig. 1a; one sees the electron and the struck-quark jet each with transverse momentum  $Q$ . This Coulomb-scattering picture is accurate in the frame of reference where  $\eta = 0$  is chosen to be the rapidity halfway between these two features.

Also of interest is the (approximate) location of the initial state quark before it was struck (the so-called “hole” fragmentation region [7]). It is a distance of order  $\ln Q$  to the left of the quark jet, because  $\ln \theta/2$  has changed by approximately that amount because of the Coulomb scattering. It is a distance  $\ln 1/x$  from the leading-proton fragments.

It is also convenient, especially theoretically, to view the same process in a collinear virtual-photon proton reference frame (cf. Fig. 1b). In such a frame there are generically no large- $p_T$  jets, at least at the level of naive, old-fashioned parton model. With QCD, there will be extra gluon initial-state and final-state radiation. Most of this will look like minijet production in collinear reference frames, but occasionally there will be extra genuine gluon jets, especially in the phase-space region between the hole and the leading quark fragments. Note that now the amount of phase-space to the right of the “hole” region is of order  $\ln Q^2$ ; the extra  $\ln Q$  amount of phase space is in the quark jet in HERA reference frames. The total phase space is evidently  $\ln Q^2 + \ln 1/x = \ln W^2$ , as it should be.



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Figure 1: Lego-plot of final-state hadrons in small- $x$  deep inelastic scattering: (a) HERA laboratory frame, and (b) collinear  $\gamma^* - p$  reference frames.

We now are ready to introduce Gribov's paradox. He viewed the same process in the laboratory frame of the nucleon, but considered for simplicity replacement of the nucleon by a large, heavy nucleus of radius  $R$ . The picture is that first there is the virtual dissociation of the virtual photon into a hadron system upstream of the target hadron. For HERA conditions and Ioffe's estimate of longitudinal distances, this is a distance of hundreds of fermis in this fixed-target reference frame. This virtual dissociation process is followed by just the geometrical absorption of the virtual-

hadron system on the nucleus. Gribov used old-fashioned (or in modern terms light-cone) perturbation theory to make the estimate, which gives a simple and utterly transparent result:

$$\sigma_T = (1 - Z_3) \pi R^2 . \quad (2)$$

Note that the estimate is for  $\sigma_T$ , not  $F_2$ , and that  $(1 - Z_3)$ , with  $Z_3$  the charge renormalization of the photon, is just the probability the photon is hadron, not photon:

$$1 - Z_3 = \frac{\alpha}{3\pi} \int \frac{ds s R(s)}{(Q^2 + s)^2} \approx \frac{\alpha}{3\pi} \bar{R} \ln \frac{1}{x} , \quad (3)$$

where  $R(s)$  is the sum of squared charges of partons, as used in describing the  $e^+e^-$  annihilation cross section. So up to logarithmic factors, the result is that  $\sigma_T$ , not  $F_2$ , is independent of  $Q^2$ . Since

$$F_2 = \frac{Q^2 \sigma_T}{4\pi^2 \alpha} , \quad (4)$$

this means the aforementioned scaling violation by an extra power of  $Q^2$ . Gribov's structure function is much too big (at least at present energies)!!

There are (at least) two ways out of the paradox. One way is, in modern jargon, "color transparency". Typically the virtual photon dissociates into a bare  $q-\bar{q}$  system which on arrival at the nucleus is a small color dipole of spatial extent  $Q^{-1}$ . It can only interact perturbatively with the target via single gluon exchange. And since the cross section goes as the square of the dipole moment, one gets  $\sigma_T$  proportional to  $Q^2$ , as is needed. Note however that the final state morphology is different from what has been given for the naive parton model; it contains two leading jets (in the virtual photon direction) and a recoil-parton jet in the proton direction, all typically with a  $p_T$  scale  $Q$  (this in the collinear  $\gamma^*$ -proton frame; cf. Fig. 2). Also the  $A$ -dependence for this mechanism is generically  $A^1$ .

The second mechanism is associated with more infrequent configurations, where the  $q$  and  $\bar{q}$  created by the virtual photon do not have large  $p_T$ , but are aligned along

the virtual-photon beam direction. This clearly leads to one particle (call it the quark  $q$ ) carrying almost all the momentum and the other (the  $\bar{Q}$ ) carrying much less. When the kinematics is worked out, one finds that the typical momentum carried by the “slow”  $\bar{Q}$  is of order  $x^{-1}$  GeV. But do note that this is still hundreds of GeV for HERA conditions, in Gribov’s fixed-target reference frame.

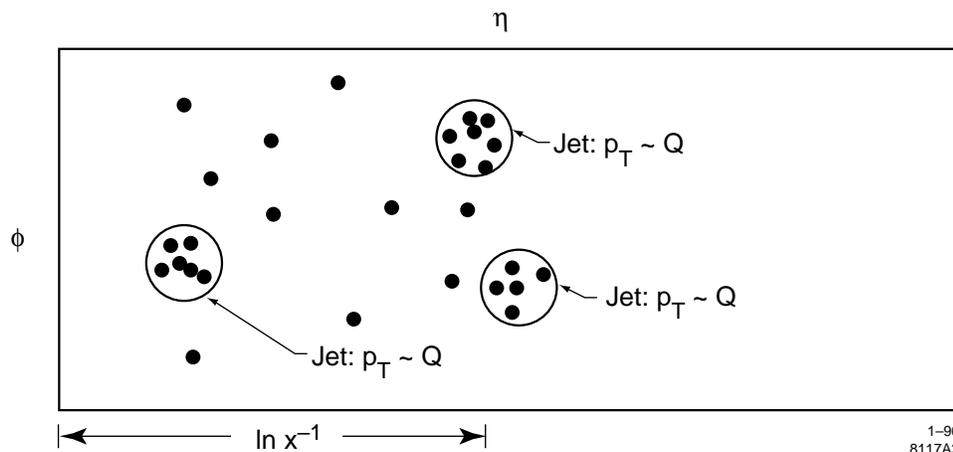


Figure 2: Lego-plot of final-state hadrons for the “color-transparency”, “Bethe-Heitler”, or “noncollinear photon-gluon fusion” mechanism at small  $x$ .

There is enough time, according to Ioffe’s basic estimate, for this “slow”  $\bar{Q}$  to evolve nonperturbatively [8], and in particular it will be found at large transverse distances from the “fast” quark, of order the hadronic size scale. (For example there is enough time and space for a nonperturbative color flux-tube to grow between  $q$  and  $\bar{Q}$ .) So on arrival at the target hadron the hadronic progeny of the virtual photon look something like a B-meson, the fast pointlike  $q$  analogous to the pointlike  $b$ -quark, and the slow structured  $\bar{Q}$  looking something like the light constituent antiquark orbiting the  $b$ .

It follows that when this configuration evolves, it should be absorbed geometrically on the target nucleus or nucleon, as assumed by Gribov. But the probability, per

incident virtual photon, that this configuration actually occurs is easily worked out to be (constant)/ $Q^2$ , so the scaling of the structure function  $F_2$  is recovered. Also, the final-state structure in collinear reference frames contains no jets, so the parton-model final state structure is recovered. The  $\overline{Q}$  final-state fragmentation products are in fact located in the “hole” fragmentation region already described. An additional expectation is that the A-dependence at small  $x$  is  $A^{2/3}$ , even at large  $Q^2$ .

### 3 Phenomenology

I am not conversant with all the details of the phenomenology. However to the best of my knowledge the main features of the data support the “aligned jet” mechanism for the bulk of the events which build  $F_2$  at small  $x$ . In particular,

1. The A-dependence of  $F_2$  at small  $x$  and large  $Q^2$  is roughly  $A^{2/3}$ ; shadowing is definitely seen and scales [9].
2. Leading dijets (in the virtual photon direction) are seen rarely, if at all, when the data is viewed in a collinear  $\gamma^*$ -proton reference frame. The final-state is “soft” most of the time [10].
3. However, in the region of sharp rise of  $F_2$ , I am not sure that these final-state properties persist as strongly. Certainly the A-dependence is untested there.

But in any case, it would appear that the most natural hypothesis is that the data on  $F_2$  is dominated by the aligned-jet mechanism at small  $x$ .

### 4 Diffraction

With this lengthy prologue, we are now ready to consider the rapidity-gap events seen at HERA. But with these preliminaries the interpretation is very simple and

direct. In particular, whenever there is a process where strong absorption occurs (transmission probability small compared to unity), there must be (elastic) shadow scattering. In this case it is the “slow”  $\bar{Q}$  which is the structured, hadronic object which gets absorbed. So we can expect it to be elastically scattered from the proton (or nucleus) as well.

What will the final state look like? The  $\bar{Q}$  does not emerge unscathed, but will physically separate from the “fast” quark  $q$ . So there will be hadronization associated with this color separation, just as in  $e^+ - e^-$  annihilation. In the lego plot of the final state, this means that a population of hadrons will be found between the fragmentation region of the quark  $q$  and the “hole” fragmentation region characteristic of the rapidity of the  $\bar{Q}$  before-and after-the elastic scattering; the mass of this hadron system is typically of order  $Q^2$ . Hadrons will *not* be found, however, in the rapidity region between the target proton (or nucleus) and the  $\bar{Q}$ .

Actually the distribution in the diffracted mass  $m$  can be inferred from the Gribov estimate, Eq. 3, because the momentum change of the  $\bar{Q}$  due to the elastic scattering is typically so small that the mass of the  $q$ - $\bar{Q}$  system is not significantly modified. The Gribov distribution associated with  $(1 - Z_3)$  is

$$\frac{dN}{dm^2} = \frac{m^2}{(Q^2 + m^2)^2} . \quad (5)$$

However this should be multiplied by the alignment probability  $(\text{constant})/m^2$ . Experimentalists prefer to use instead of the diffracted mass the scaled quantity beta:

$$\beta = \frac{Q^2}{m^2 + Q^2} . \quad (6)$$

Therefore

$$\frac{dN}{d\beta} \sim (\text{const}) . \quad (7)$$

A constant beta distribution, as estimated here, is in rough agreement with the data [11, 12], especially given the semiquantitative nature of these arguments. How-

ever there does appear to be an excess at small beta (large diffracted mass), which requires an extension of this mechanism such as inelastic diffraction of the constituent quark.

The other dependence of relevance is that of the  $W^2$  dependence of the ratio of the diffractive component to the total. It should be (at fixed  $Q^2$ ) the same as the  $s$ -dependence of  $\sigma_{el}/\sigma_{tot}$  for hadron-hadron interactions. Donnachie and Landshoff [13] successfully fit the total and elastic cross section data with a Pomeron Regge pole, namely a pure power-law dependence of  $\sigma_{tot}$ . The behavior is  $s^{0.08}$ . This should also be the case (up to a logarithm associated with the shrinkage of the elastic peak) for  $\sigma_{el}/\sigma_{tot}$ . The  $W^2$  dependence of  $F_2$  in this picture (at fixed  $Q^2$ ) should also be  $(W^2)^{0.08}$ ; this number seems on the low side [11, 12] but there is still controversy and uncertainty on what the fixed- $Q^2$  exponent really is. In any case, the fraction of rapidity-gap events should not be a strong function of either  $Q^2$  or  $W^2$ .

Finally, the absolute magnitude of the ratio of gap/no-gap events, predicted to be  $\sigma_{el}(\overline{Q} - p)/\sigma_{tot}(\overline{Q} - p)$ , is reasonable [10, 14]—between 5% and 10%.

Omitted in this line of argument, but certainly possible to include, are the contributions of diffraction-dissociation of  $\overline{Q}$  and/or target proton/nucleus. Although a year ago [15] I essentially assumed (in the language of this talk) that the  $\overline{Q}$  diffraction dissociation might be dominant, this year it seems more unreasonable—especially in the light of the data that appeared in the intervening time. It does seem that excitations of constituent quarks are not seen in spectroscopy, and that may be reflected in the HERA diffractive data. The fraction of rapidity-gap data for which the proton dissociates should be more or less characteristic of the ratio of single dissociation to elastic scattering (25% or so) seen in  $p - \overline{p}$  collisions. This should be soon checked at HERA.

It certainly is possible to sharpen this line of thinking and make more crisp predic-

tions [16]. And the recent ideas of Buchmuller and Hebecker [17] bear much similarity to this picture. I apologize for not having done more myself. But the bottom line of this line of thinking, worth emphasizing here again, is that the important mechanism for the small- $x$  final-state structure is not to be found within perturbative QCD. It is not short-distance, weak-coupling dynamics that counts, but large-distance, strong-coupling, strong-absorption dynamics that is at the heart of the matter. There need be nothing more pointlike about the mechanism producing the diffractive final states than the mechanism responsible for elastic proton-proton scattering.

## 5 What about (BFKL) Hard Diffraction?

The first mechanism for the small- $x$  dynamics which was discussed in Section 2, i.e. “color-transparency” or “QCD Bethe-Heitler” (or noncollinear photon-gluon fusion), must at some level also be present. For the reasons already cited, I suspect it is at no more than the 10%–20% level. But that is only a guess. The best way to isolate it experimentally is via the 3-jet final state morphology exhibited in Fig. 2. This is the seed kernel for building at high energies and fixed  $Q^2$  the BFKL  $W^2$  dependence [18] via production of extra gluons into the phase space, gluons typically also carrying  $p_T$  of order  $\sqrt{Q^2}$ . The  $W^2$  dependence to be expected is much stronger, of order  $(W^2)^{0.4}$ .

Open questions regarding the relevance of this mechanism for HERA include

1. whether the normalization of the lowest-order kernel is large enough,
2. how much room there is in the available HERA phase space for building up the power-law behavior, and
3. whether the scheme is consistent: there exist criticisms regarding “diffusion into the infrared”, as well as claims [19, 20, 21, 22] that more careful attention must be paid to energy-conservation constraints within the multi-Regge kinematics.

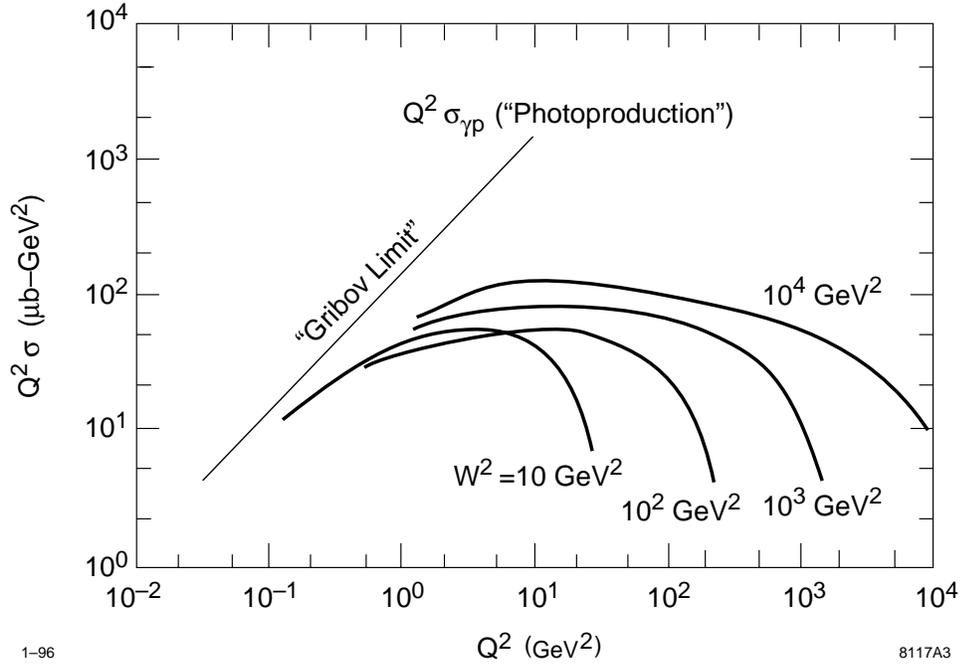


Figure 3: A log-log sketch of  $F_2$  vs  $Q^2$  at various fixed values of  $W^2$ .

An observed trend toward the BFKL  $W^2$  dependence would clearly be of fundamental importance, implying a new class of nonperturbative, absorptive effects going far beyond those we used in the previous section to interpret existing data. I here make only the most modest suggestion, regarding how to plot the data. I am a firm believer in the importance of searching for the optimum way of presenting data, the way which most directly highlights what is important. My suggestion in this case is to plot  $\log F_2$  versus  $\log Q^2$  at fixed  $W^2$ . A sketch of what I mean is shown in Fig. 3.  $W^2$  is chosen rather than  $x^{-1}$  because there is no longer scaling in the small- $x$  region, and because the nonscaling depends on gluon emission, which probably is more dependent on the amount of available phase space than anything else. (This is certainly the case for BFKL). The logarithmic scales allow a clear view of how the photoproduction limit is approached, and above that limit by some not-so-well-defined factor is the

Gribov bound, unmodified by any damping due to color-transparency or aligned-jet configurations. Existing data for not large  $W^2$  show a curve of  $\log F_2$  vs  $\log Q^2$  which is concave down. If any part of the curve becomes at high  $W^2$  concave up, this would be to me a signal for “BFKL behavior”, because it is the only way the Gribov bound can be reached. The important regime for HERA is, as is well-known, moderate  $Q^2$  ( $0.5 \text{ GeV}^2$ – $15 \text{ GeV}^2$ ) at the highest  $W^2$  attainable.

My own favorite guess [23] on how things will turn out is that the curves will remain concave down, but that the  $W^2$  dependence of the maximum of  $F_2(Q^2, W^2)$  for given  $W^2$  will behave more or less like BFKL.

## 6 Acknowledgment

It has been some time since I last visited ITEP, and as always it has been a most pleasant and stimulating experience. I thank Boris Ioffe and his colleagues for their warm hospitality.

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