Rapidity Gaps Between Jets in γp Collisions at HERA

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(April 30, 1998)

Diffractive scattering in the presence of a large momentum transfer is an ideal place to study the pomeron in a region accessible to perturbative QCD calculations. Such studies have focused on 'rapidity gaps between jets'. We review the results of the H1 and ZEUS collaborations at HERA, and discuss the problems associated with this approach. We propose a new approach, in which we study double dissociation at high $|t|$. We conclude that this more inclusive study avoids many of the drawbacks of measurements involving gaps between jets.

I. INTRODUCTION

The strong interaction is at present understood in two distinct and separate regimes: the short range, hard partonic interactions to which perturbative QCD calculations are applicable, and the long range, soft interactions described by the phenomenology of Regge theory. Both frameworks have proved outstandingly successful, and yet both have remained essentially disconnected; QCD has as yet been unable to "reproduce" Regge theory, as it must if it is to be regarded as the complete theory of the strong interaction.

In the Regge region the scattering process is described in terms of the t-channel exchange of mesons and, at higher energy, by the pomeron, which in modern language has come to mean any strongly interacting colourless object with vacuum quantum numbers. The contribution of such processes to the total DIS cross section has been measured in detail by the ZEUS and H1 collaborations and quantified in terms of the diffractive structure function F_2^D [1] [2] [3]. Tantalising departures from Regge theory expectations have been seen and may signal the onset of QCD corrections to the Regge picture as the pomeron is forced into regions of phase space where pQCD is relevant.

A natural first step towards any eventual QCD understanding of Regge behaviour would seem to be a pQCD understanding of the pomeron, and in recent years much progress has been made. In particular, the 'rapidity gaps between jets' process suggested for study by Mueller & Tang [4] restricts the experimental phase space to a region where QCD, e.g. in the form of the leading logarithmic approximation (LLA) of BFKL [5], is applicable. In this paper we review the 'rapidity gaps between jets' measurements made by the H1 and ZEUS collaborations at HERA. Similar measurements have been made at the Tevatron experiments, [6] [7], and all experiments certainly see a signal for a gap producing mechanism above the expectation from normal QCD processes. The 'rapidity gaps between jets' approach, however, falls short of providing a quantitative test of the theory, which in the form of the LLA is itself far from complete [8]. With this in mind, we present a new, more inclusive experimental approach [9], which will provide data better suited for precise quantitative comparisons with theory.

II. RAPIDITY GAPS BETWEEN JETS IN γP COLLISIONS AT HERA

The cross section for lepton-proton collisions at HERA is dominated by photoproduction, where the lepton radiates a quasi-real photon which then interacts with the proton. In this case, the photon behaves more like a hadronic object, described in terms of parton distribution functions, and a parton from the photon interacts with a parton from the proton. The generic "QCD Pomeron" scattering process at HERA is shown in figure 1. For colour singlet exchange there is no colour connection between the outgoing partons and so these events are characterised at the hadron level by an absence of energy flow (or the existence of a rapidity gap) between the two systems X and Y. By demanding jets in both the X and Y systems, we ensure that the momentum transfer across the rapidity gap is sufficiently large that pQCD is applicable. The experimental signature for this process is shown in figure 2b.

A rapidity gap can also be produced in events where the hard scatter is mediated by an object with net colour, i.e. a quark or gluon, by multiplicity fluctuations in the hadronic final state. In order to distinguish between these and genuine colour singlet mediated scattering events, the 'gap fraction' is introduced. The 'gap fraction', $f(\Delta\eta)$, is defined as the proportion of events containing two or more high E_T jets for which there is a gap in rapidity between the two highest E_T jets as a function of the jet - jet separation $\Delta\eta$. For processes involving the exchange of objects with net colour, the naive expectation (the assumption that the multiplicity fluctuations obey simple Poisson statistics) is for $f(\Delta\eta)$ to decrease exponentially with increasing $\Delta\eta$. If colour singlet exchange also plays a role, the gap fraction is expected to level off at some value of $\Delta\eta$.

The gap fractions measured by H1 and ZEUS, fully corrected for detector effects, are shown in figure 3. A detailed description of the event selection and correction procedures can be found elsewhere [10] [11].

In the case of H1, photoproduction events were selected by detecting the scattered positron in the electron tagger of the H1 luminosity system, located 33 m from the interaction point in the direction of the outgoing positron beam. This restricts the virtuality of the photon to $Q^2 < 0.01$ GeV^2. The photon - proton centre of mass energy is restricted to the range $158 < W < 247$ GeV to avoid regions of low electron tagger acceptance. In the ZEUS analysis, photoproduction events were selected by requiring no scattered positron candidate in the main calorimeters, restricting the virtuality of the photon to $Q^2 < 4$ GeV^2. The photon - proton centre of mass energy is restricted to the range $135 < W < 280$ GeV.

In the H1 (ZEUS) analysis, jets are found using a cone algorithm with cone size 1.0 and $E_T^{jet} > 4.5$ (5) GeV. Jet pseudo-rapidities ($\eta = -\ln\tan[\theta/2]$) are restricted to the range $-2.82 < \eta < 2.35$ ($\eta < 2.5$), ensuring that the jet cones are completely contained within the calorimeters. A gap event is defined as an event in which there is no calorimeter cluster of energy $E > 400(250)$ MeV in the rapidity interval between the edges of the cones containing the two highest E_T jets.

In summary, the gap fraction is observed to fall exponentially throughout the region $2.0 < \Delta\eta < 3.5$, whereas an excess of events above the exponential fall off is observed in the range $3.5 < \Delta\eta < 4.0$. Integrated over this latter interval, the measured value of $f(\Delta\eta)$ lies more than two standard deviations above the exponential fall off. This excess can be interpreted as the result of the exchange of a strongly interacting colour singlet object.

III. THE DRAWBACKS OF THE 'GAPS BETWEEN JETS' APPROACH

The drawbacks of the gaps between jets approach as a means of testing the BFKL formalism are related to two experimental limitations. The Mueller & Tang cross section for colour singlet exchange has the form [4]

$$\frac{d\hat{\sigma}}{dt} = \frac{(\alpha_s C_f)^4 \pi^3}{4t^4} \frac{e^{2\omega_0 y}}{[\frac{7}{2}\alpha_s C_A \zeta(3) y]^3} \tag{1}$$

where y is the rapidity difference between the outgoing partons from the hard scatter. The key feature is the exponential rise in the cross section with y. This means that the larger the experimental reach in rapidity, the clearer the characteristic BFKL rise in the cross section becomes. The ω_0 factor in the exponent is calculable in the theory. In Regge language it is the intercept of the hard pomeron. At leading order BFKL $\omega_0 = \frac{12 ln 2\alpha_s}{\pi}$, although there are large next to leading order corrections [8] which make this quantity theoretically uncertain. Also note that at leading order, the scale of α_s is unknown, and hence α_s becomes essentially a free parameter to be fit to data. A major drawback of the gaps between jets approach is the inability to access large rapidity differences. If two jets of cone radius 1 unit of rapidity must be contained within the calorimeters, and a typical calorimeter spans no more than 8 units of rapidity, the reach in y is clearly limited. Furthermore, the requirement of two jets with $E_t > 5$ GeV restricts $|t| > 25$ GeV^2, whereas the pQCD cross section may well hold to $|t| \sim 1$ GeV^2. We are therefore throwing away the overwhelming majority of the events available for analysis. It is clear that there should be a better way to investigate this region of 'high $|t|$ diffraction'.

IV. A NEW APPROACH AT HERA

A solution to both these problems has been suggested by Cox & Forshaw [9]. The hadronic final state is split by the largest rapidity gap in the event into two hadronic systems X and Y (figure 1). In terms of the jet measurement, system X is the backward, or photon side jet and Y is the forward or proton side jet. The scattered electron is tagged in the electron tagger, limiting Q^2 to < 0.01 GeV^2. The entire kinematics of the event are constrained by the measurement of the scattered electron, giving the 4-vector of the photon, and the 4-vector of the X system, which at HERA is boosted into the detector and hence well measured. We now have the advantage that we can allow the Y system to move completely outside the detector, since we do not need to measure it, increasing the largest observable gap size to over 7 units of rapidity.

With the hadronic final state split into two systems as described above, the kinematics of the process are completely described by the differential cross section $\frac{d^4\sigma}{dx_{\mathbb{P}}\, dM_y\, dt\, dW^2}(\gamma p \to XY)$, where $x_{\mathbb{P}} = \frac{\gamma.(P-Y)}{\gamma.P} \simeq \frac{M_x^2 - t}{W^2}$, $t = (\gamma - X)^2$ and W is the γp centre of mass energy.

Events with gaps are characterised by $M_X, M_Y \ll W$ and so the sample is reduced by insisting that $M_Y \leq M_{Y\text{cut}}$. This cut can be implemented without needing a very precise measurement of the system Y. The sample is further restricted to the region of high $|t|$ by requiring $|t| \geq t_{min}$, with t_{min} measured as described above, and determined primarily by experimental resolution. The resulting sample is the sample of interest. This way of defining the sample has the very important advantage that it is easy to implement theoretically and is quite insensitive to hadronisation effects which define the edges of the systems X and Y. An interesting observable is $\frac{d\sigma}{dx_{\mathbb{P}}}(\gamma p \to XY)$ at fixed W^2. Cox & Forshaw show that $\frac{d\sigma}{dx_{\mathbb{P}}} \propto (\frac{1}{x_{\mathbb{P}}})^{2\omega_0}$, with a weak dependence on the photon parton distribution functions. It should be noted that this prediction is dependent only on the exponential form of equation (1), not the details of the leading order BFKL equation which gives the prediction for the pomeron intercept ω_0. This measurement therefore offers the possibility of measuring directly the hard pomeron intercept, 'to all orders' in the theory.

The Mueller & Tang colour singlet cross section has been implemented into the HERWIG 5.9 Monte Carlo [12], allowing a simulation up to hadron level including the background expected from fluctuations from non colour singlet photoproduction processes. The $x_{\mathbb{P}}$ distribution at fixed W is shown in figure 4 for both standard photoproduction and photoproduction with colour singlet exchange, for $W = 250$ GeV, $0 < M_y < 10$ GeV and $|t| > 4$ GeV^2. For the colour singlet sample, ω_0 is an input parameter into HERWIG, here chosen to be 0.61. Also shown in figure 4 (b) is the result of a $\frac{1}{x_{\mathbb{P}}}^{2\omega_0}$ fit for ω_0 to the measured $x_{\mathbb{P}}$ distribution.

V. CONCLUSIONS

Results from CDF [6], D0 [7], ZEUS [10] and H1 [11] all show evidence of an excess of gap events at high $|t|$ over what would be expected from non-colour singlet exchange processes. The data, however, are not at present sufficient to allow precise quantitative comparisons between theoretical models. The new approach suggested by Cox & Forshaw [9] avoids many of the drawbacks of the 'gaps between jets' measurements, and provides a well defined cross section for comparison with theory.

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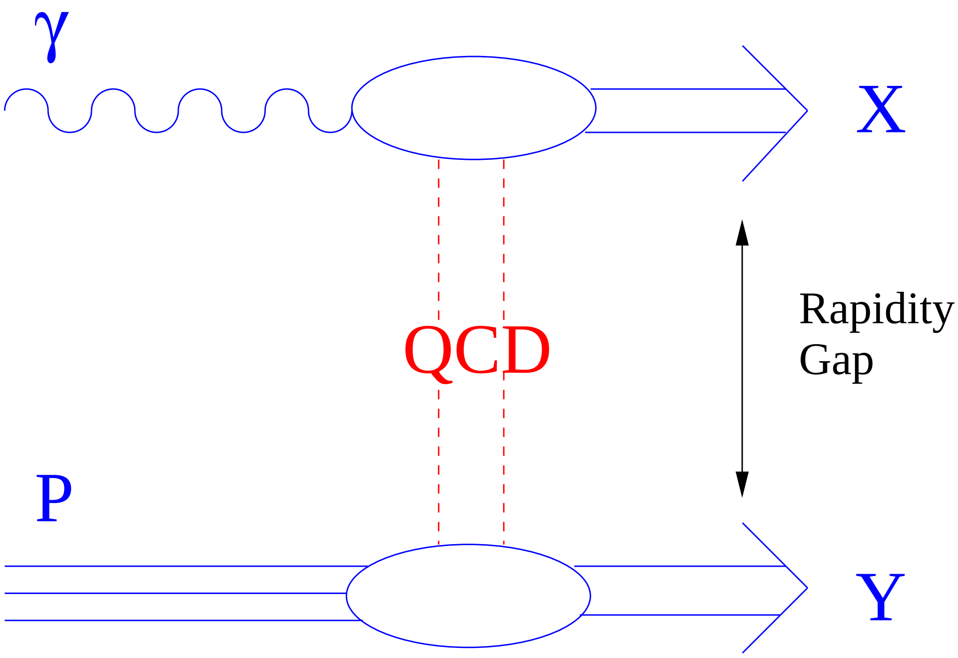

FIG. 1. The generic "QCD pomeron" scattering process in photoproduction at HERA

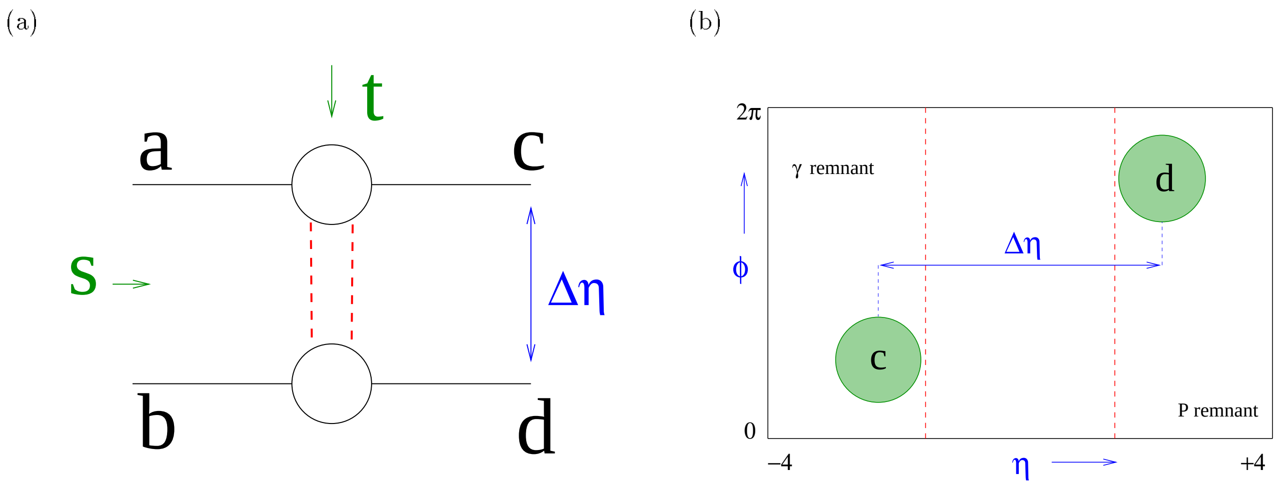

FIG. 2. The underlying hard scattering process at parton level (a) and its signature at detector level (b). Parton 'a' is from the incoming photon and parton 'b' from the proton.

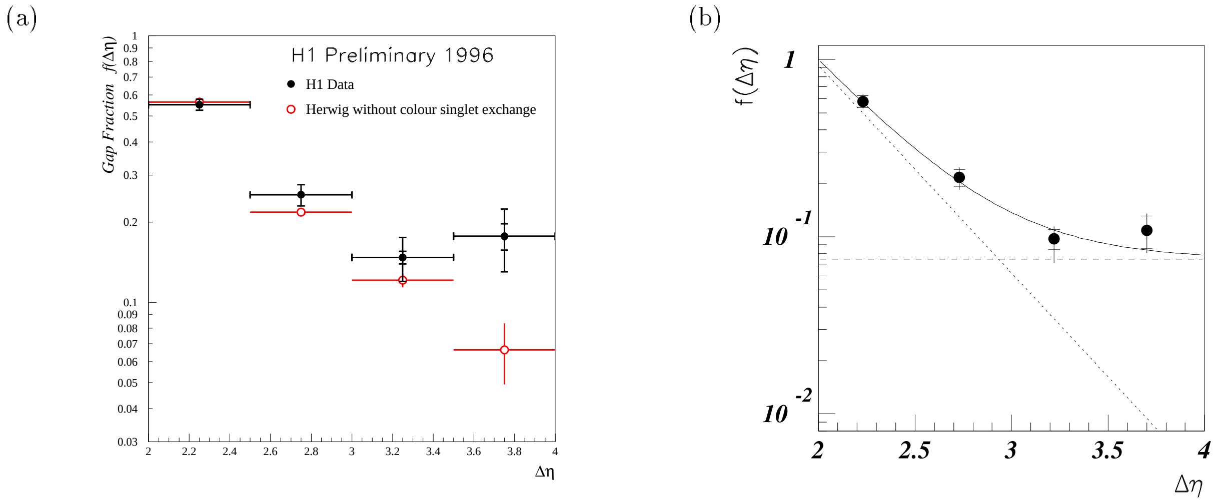

FIG. 3. The corrected gap fraction $f(\Delta\eta)$. H1 1996 data (a) are solid points. The inner error bars show the statistical errors and the outer error bars show the sum in quadrature of the statistical and systematic errors. The prediction of the HERWIG simulation without a colour singlet exchange component is shown, together with statistical errors, as the open points. ZEUS 1994 data (b) are solid points, compared with a fit of an exponential plus a constant (dashed and solid lines)

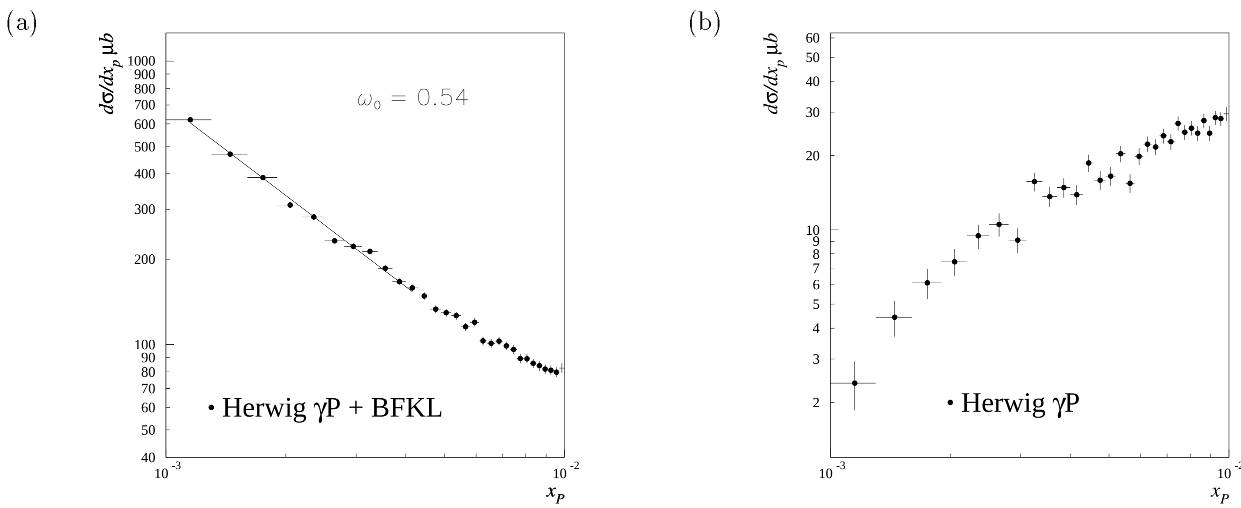

FIG. 4. $\frac{d\sigma}{dx_{\mathbb{P}}}(\gamma p \rightarrow XY)$ at fixed W for HERWIG colour singlet + photoproduction (a) and photoproduction alone (b), for a luminosity of $\sim 2.5pb^{-1}$. Also shown in (a) is the value of ω_0 recovered from a $\frac{1}{x_{\mathbb{P}}}^{2\omega_0}$ fit shown as the solid line.