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Rapidity Gaps in DIS through Soft Colour Interactions

A. Edin¹, G. Ingelman^{1,2}, J. Rathsman¹

¹Dept. of Radiation Sciences, Uppsala University, Box 535, S-751 21 Uppsala, Sweden

²Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22603 Hamburg, Germany

Abstract

We present a new mechanism for the creation of large rapidity gaps in DIS events at HERA. Soft colour interactions between perturbatively produced partons and colour-charges in the proton remnant, modifies the colour structure for hadronization giving colour singlet systems that are well separated in rapidity. An explicit model is presented that, although the detailed results depend on the initial state parton emission, can describe both the observed rapidity gaps and, in addition, the forward energy flow in an inclusive event sample.

Résumé

A striking feature of deep inelastic scattering (DIS) at the HERA ep collider is the relatively large fraction ($\sim 10\%$) of events with a rapidity gap [1, 2], i.e. with no particles or energy in a large rapidity region close to the proton beam direction. These events can be interpreted in terms of hard scattering on a pomeron (\mathbb{P}) [3], a colour singlet object exchanged in a Regge description of diffractive interactions. Although explicit such models (see e.g. [4, 5]) can describe the salient features of the observations, there is no satisfactory understanding of the pomeron and its interaction mechanism.

Here, we present a new and alternative way to interpret the rapidity gap phenomenon, without using the concept of a pomeron. Instead, our model is based on normal DIS parton interactions, with perturbative QCD (pQCD) corrections, complemented with the new hypothesis that non-perturbative soft colour interactions occur and change the colour structure such that when normal hadronization models are applied rapidity gaps may arise.

At small Bjorken- x ($10^{-4} - 10^{-2}$), where the rapidity gap events are observed, the boson-gluon-fusion (BGF) process $\gamma g \rightarrow q\bar{q}$ (cf. Fig. 1) occurs frequently.

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The cross section is calculable in first order QCD, with the conventional requirement $m_{ij}^2 > y_{cut}W^2$ on any pair ij of partons to avoid soft and collinear divergences. Higher order pQCD emissions can be taken into account approximately through parton shower evolution from the final partons and the incoming one (as illustrated with one emitted gluon in Fig. 1). In the following non-perturbative hadronization process one usually considers the formation of colour singlet systems (clusters, strings) that subsequently break up into hadrons. In the conventional Lund model [6] treatment, a BGF event gives two separate strings from the q and \bar{q} to the proton remnant spectator partons (Fig. 1a), thereby causing particle production over the whole rapidity region in between. This treatment is implemented in the Monte Carlo LEPTO [7], which describes most features of HERA DIS events.

This conventional treatment assumes that the colour structure, i.e. the string topology, follows exactly the perturbative phase with no further alternations. Our main assumption here is that additional non-perturbative soft colour interactions (SCI) may occur. These have small momentum transfers, below the scale Q_0^2 defining the limit of pQCD, and do not significantly

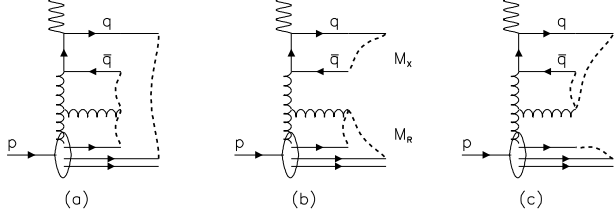


Figure 1. The string configuration in a DIS boson-gluon-fusion event: (a) conventional Lund string connection of partons, and (b, c) after reconnection due to soft colour interactions.

change the momenta from the perturbative phase. However, SCI will change the colour of the partons involved and thereby change the colour topology as represented by the strings. Thus, we propose that the perturbatively produced quarks and gluons can interact softly with the colour medium of the proton as they propagate through it. This should be a natural part of the processes in which ‘bare’ perturbative partons are ‘dressed’ into non-perturbative quarks and gluons and the formation of the confining colour flux tube in between them.

Lacking a proper understanding of such non-perturbative QCD processes, we construct a simple model to describe and simulate these interactions. All partons from the hard interaction (electroweak + pQCD) plus the remaining quarks in the proton remnant constitute a set of colour charges. Each pair of charges can make a soft interaction changing only the colour and not the momenta, which may be viewed as soft non-perturbative gluon exchange. As the process is non-perturbative the exchange probability cannot be calculated so instead we describe it by a parameter R . The number of soft exchanges will vary event-by-event and change the colour topology of the events such that, in some cases, colour singlet subsystems arise separated in rapidity. In the Lund model this corresponds to a modified string stretching as illustrated in Figs. 1bc, where (b) can be seen as a switch of anticoulour of the antiquark and the diquark and (c) as a switch of colour between the two quarks. This kind of colour switches between the perturbatively produced partons and the valence partons in the proton are of particular importance for the gap formation.

Of relevance is also the modelling of the non-perturbative proton remnant system, i.e. the proton ‘minus’ the parton entering the hard scattering process. If that parton is a u or d quark, the remnant has previously been modelled as a valence diquark which, as a colour anti-triplet, will be an endpoint of a string. Here we introduce a modified treatment of the remnant

three valence quarks, which are split into a quark and a diquark in the conventional way [7], plus the partner antiquark from the sea to conserve flavour quantum numbers. These three partons form two colour singlet systems (strings) together with the scattered quark (and extra gluons). This two-string configuration for sea-quark-initiated processes provides a better continuity to the two-string gluon-induced BGF events.

Rapidity gaps have been experimentally investigated [1, 2] through the observable η_{max} giving, in each event, the maximum pseudo-rapidity in the detector where an energy deposition is present. (With $\eta = -\ln \tan \theta/2$ and θ the angle relative to the proton beam, $\eta > 0$ is the proton hemisphere in the HERA lab frame.) Fig. 2 shows the distribution of this quantity as obtained from our model simulations for $7.5 < Q^2 < 70$ and $0.03 < y < 0.7$.

The maximum rapidity parton from the BGF matrix element (Fig. 2a) can be central or even in the electron beam hemisphere depending on the phase space allowed by y_{cut} . For $y_{cut} = 0.005$, which has been shown to be theoretically sound [8], about 10 % are BGF events. The small $y_{cut} = 0.0001$ results [7] in an adjustment of the cut-off such that the total (Born) cross section is saturated with 2 + 1-jet events, giving $\sim 50\%$ BGF events. The partons can here emerge with a large rapidity gap relative to the spectator partons at large η outside the detector coverage (beam pipe). However, this gap does not survive to the hadron level as shown by the large effects from parton showering and hadronization. The introduction of soft colour interactions have a large effect on the η_{max} distribution, as demonstrated in Fig. 2b. Still, our SCI model is not very sensitive to the exact value of the parameter R . In fact, increasing R above 0.5 gives almost no effect. Once a colour exchange with the spectator has occurred additional exchanges among the partons need not favour gaps and may even reduce them. In the following we use $R = 0.2$, which can be seen as the strong coupling $\alpha_s(0.5 GeV)/\pi \approx 0.2$ at a typical small momentum transfer representative for the region below the perturbative cutoff $Q_0^2 \sim 1 GeV^2$.

One should note that the basic features of this distribution, the height of the peak and the ‘plateau’, is in reasonable agreement with the data [1, 2]. (A direct comparison requires taking detailed experimental conditions into account.) Selecting events with rapidity gaps similar to the H1 definition (i.e. no energy in $6.6 > \eta > \eta_{max}$ where $\eta_{max} < 3.2$) gives the full curve in Fig. 2b, also in basic agreement with data [2].

The exact gap probability does, however, depend on the details of the higher order parton emission treatment. In particular, the cut-off Q_0^2 for the parton

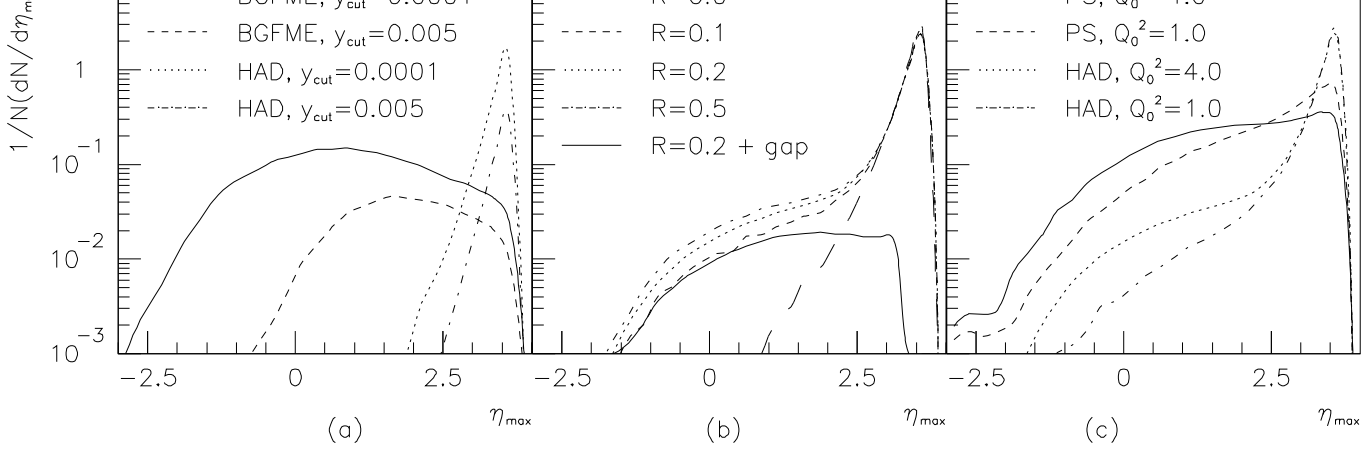


Figure 2. Distribution of maximum pseudorapidity (η_{max}). (a) Partons from boson-gluon-fusion matrix element (BGFME) with cut-off y_{cut} , and hadrons (HAD) after parton showers and string hadronization (with improved remnant sea quark treatment). (b) Hadron level after colour reconnection with probability parameter R for all events and those satisfying the ‘gap’ definition (full line). (c) Parton level (PS) and hadron level (HAD) for different initial state parton shower cut-off values Q_0^2 .

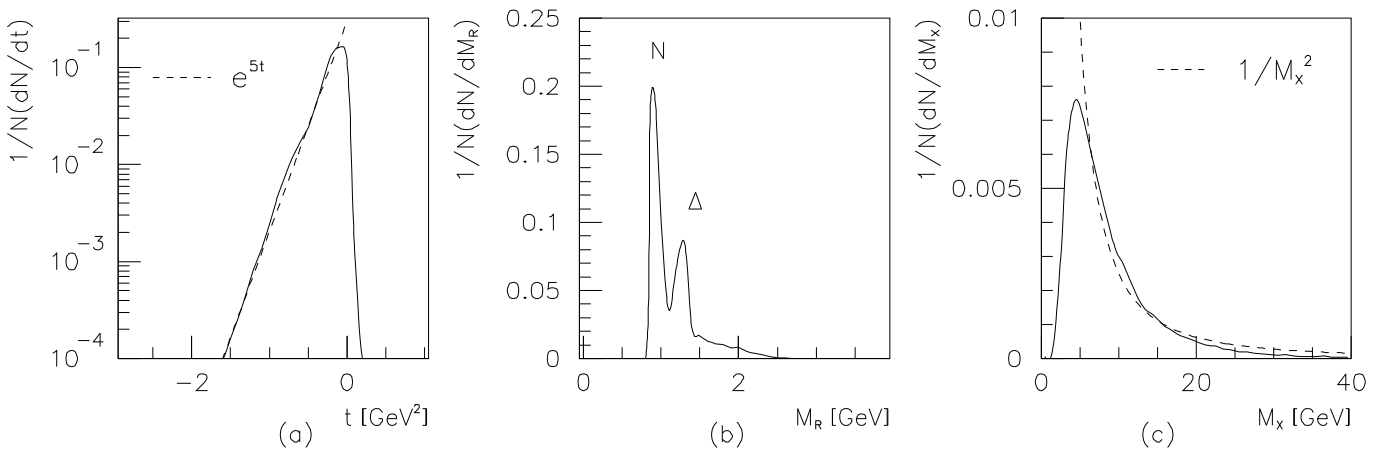


Figure 3. Distributions for the selected rapidity gap events, i.e. with no energy in $6.6 > \eta > \eta_{max}$ and $\eta_{max} < 3.2$: (a) squared momentum transfer t from incoming proton to remnant system R ; (b,c) invariant masses of the forward remnant system M_R and of the produced central system M_X (cf. Fig. 1).

shower is rather important. Choosing a value close the hadronic mass scale $\sim 1 \text{ GeV}^2$ tends to produce too much radiation at large rapidity such that the gaps are partly destroyed. A value of 4 GeV^2 for the limit of pQCD, as in many parton density parametrizations, reduces such emissions and larger gaps thereby arise after SCI (Fig. 2c).

In this context one should note that the leading logarithm GLAP evolution need not be correct when applied to the simulation of exclusive parton final states in a parton shower. It is derived for not-too-small x

and only for the inclusive case, i.e. for the evolution of the parton density, and sums over all emissions such that important cancellations can be exploited. It is not clear whether this formalism is fully applicable also to exclusive final states. It seems likely that it gives the correct mean behaviour, but it may not properly estimate the fluctuations that may occur in the emission chain. Some events may therefore have less parton radiation than estimated in this way and these would favour the occurrence of rapidity gaps.

Further features of our model are shown in Fig. 3,

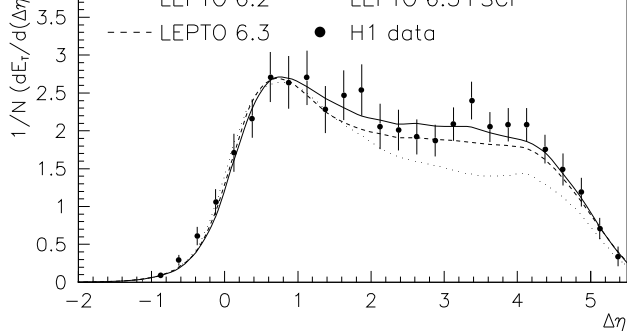


Figure 4. *Transverse energy flow versus $\Delta\eta = \eta - \eta_{q/QPM}$, i.e. lab pseudorapidity relative to the current direction in QPM kinematics, for events with $x < 10^{-3}$. The curves are from the earlier Monte Carlo model (6.2), with improved parton shower and sea quark treatment (6.3) and, in addition, with soft colour interactions (6.3+SCI).*

where the resulting distributions in momentum transfer t and mass of the remainder system R and the produced system X (cf. Fig. 1) are displayed for the selected gap events. Although the model makes no particular assumptions or requirements on these quantities, their distributions are similar to those of diffractive interactions. This applies to the essentially exponential t -dependence, $1/M_X^2$ dependence and the M_R system being dominated by the proton with some Δ resonance contribution. Thus, with a gap definition suitable for selecting diffractive interactions, our model shows the same general behaviour as models based on pomeron and other Regge exchanges. However, the detailed behaviour depends on the gap definition. Requirements of a large gap that extends very forward in rapidity introduces a kinematical bias against large values of t and M_R . The $1/M_X^2$ behaviour is explained by the $1/s_{q\bar{q}}$ dependence of the BGF matrix elements, but is distorted at large M_X by requiring the gap to extend into the central rapidity region. Thus, by varying the gap definition or observing the forward-moving R -system, one may find observable differences between the two kinds of models.

The rate of gap events in the model is essentially independent of the DIS kinematical variables x and Q^2 . This is a natural consequence of the assumed factorization of the SCI relative to the hard perturbative interactions. Some small variation may still occur since the parton shower details depends on x, Q^2 .

The observed quantity $F_2^D(\beta, Q^2)$ [2] can be interpreted as the pomeron F_2 structure function [9] with conventional QCD evolution of partons with momentum fraction β in the pomeron [10]. Having no pomeron in our model, one should instead consider the

ground for the models.

An observable which gives complementary information relative to the rapidity gaps is the forward transverse energy flow. Whereas substantial initial state parton radiation spoils the rapidity gaps, it helps to describe the high level of the forward energy flow. It is therefore a highly non-trivial test of any model that both these observables can be accounted for. As shown in Fig. 4, the E_T -flow data [11] can be well described by our new model. The two-string configurations from the improved sea quark treatment contributes to enhancing the energy flow. This is also the case for the SCI, which can lead to configurations where the string goes ‘back and forth’ producing more energy per unit rapidity.

In conclusion, we have suggested a new mechanism for the production of events with rapidity gaps. The basic assumption is that soft colour interactions may occur after the short space-time perturbative phase. This modifies the colour structure for hadronisation giving colour singlet systems that are separated in rapidity. A detailed model has features that are characteristic for diffractive scattering and can qualitatively account for the rapidity gap events observed in DIS at HERA.

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