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Soft Colour Interactions as the Origin of Rapidity Gaps in DIS

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Abstract

We introduce soft colour interactions as a novel mechanism to understand the observed events with large rapidity gaps in *ep* collisions at HERA. Colour exchanges between produced partons and colour-charges in the proton remnant modifies the colour structure for hadronization, such that colour singlet systems may appear well separated in rapidity. Our explicit model show characteristics of diffractive scattering, although no explicit pomeron dynamics have been introduced, and for non-gap events an increased forward energy flow gives agreement with data.

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In deep inelastic scattering (DIS) at the HERA *ep* collider a relatively large fraction ($\sim$ 10%) of events have been observed [1,2] to have a rapidity gap, i.e. 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 ($I\!P$) [3], a colour singlet object exchanged in a Regge description of diffractive interactions. In particular, models (see e.g. [4,5]) with a factorization of a pomeron flux and a pomeron-particle hard scattering cross section, using parton density distributions in the pomeron, can describe the salient features of the observations. Nevertheless, there is no satisfactory understanding of the pomeron and its interaction mechanism.

A main conceptual problem is whether the scattering is on a preformed colour singlet object ($I\!P$). This need not be the case since soft interactions could take place with the proton both before and after the hard scattering in such a way that a colour singlet system is formed leaving a well separated forward proton (or small-mass system). In the spirit of the latter scenario we have suggested [6] a novel way to interprete the rapidity gap phenomenon, without using the concept of a pomeron.

Here we present our model, which is based on the new hypothesis that soft colour interactions change the hadronization such that rapidity gaps occur in the final state. The starting point is the normal DIS parton interactions, with perturbative QCD (pQCD) corrections, giving a state of partons to be hadronized. By assuming that these partons undergo non-perturbative soft colour interactions the colour structure will change 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) constitutes a substantial part of the cross-section. This process 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 [7] 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 used in the Monte Carlo LEPTO [8], which describes most features of HERA DIS events.

This conventional treatment assumes that the colour structure, i.e. the string topology, follows exactly the colour ordering from the perturbative phase with no further alterations. 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 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

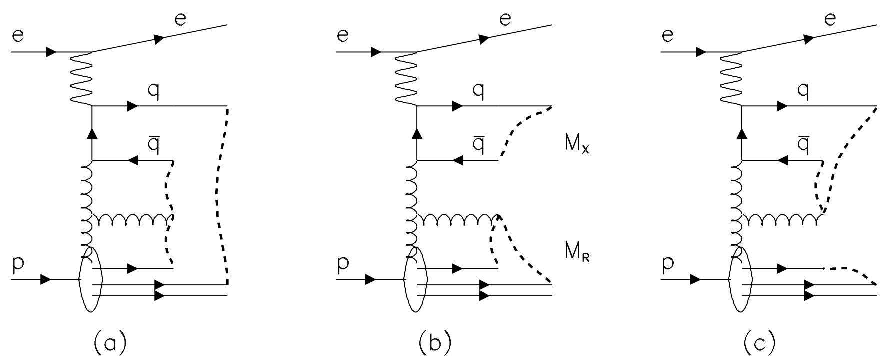

FIG. 1. The string configuration in a DIS boson-gluon-fusion event: (a) conventional Lund string connection of partons, and (b,c) after reconnection due to soft colour interactions.

'dressed' into non-pertubative 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 for a pair cannot be calculated so instead we describe it by a phenomenological 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 anticolour between 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 partons in the proton remnant are of particular importance for the gap formation.

Rapidity gaps have been experimentally investigated [1,2] through the observable η_{max} giving, in each event, the maximum pseudo-rapidity where an energy deposition is observed. (With $\eta = -\ln\tan\theta/2$ and θ the angle relative to the proton beam so that $\eta > 0$ 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 $0.03 < y < 0.7$, corresponding to the experimental conditions. In addition, the limit $\eta_{max} < 3.65$ in the H1 detector is taken into account. Clearly, the introduction of soft colour interactions ($R > 0$) have a large effect on the $\eta_{\rm max}$ distribution. Still, our SCI model is not very sensitive to the exact value of the parameter R. In fact, increasing R above 0.5 does not give an increased gap probability, but may actually decrease it depending on the details of the colour exchanges in the model. This is intuitively understandable, since once a colour exchange with the spectator has occured additional exchanges among the partons need not favour gaps and may even reduce them. In the following we use $R = 0.2$. This value may be seen as the

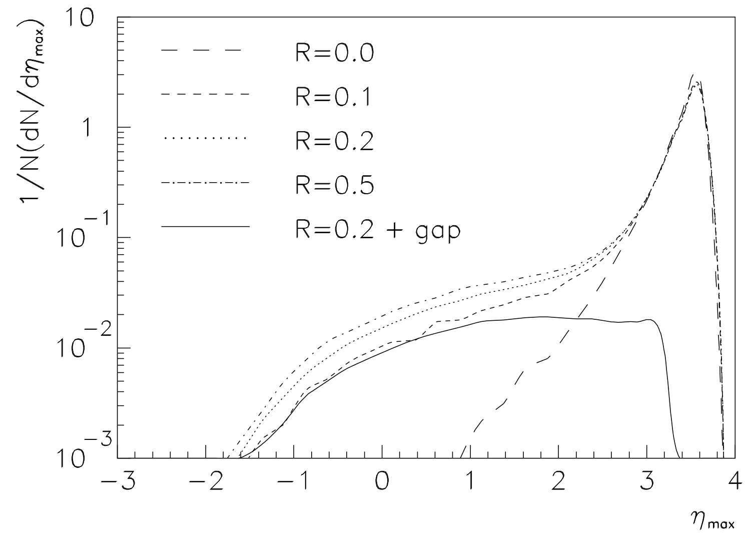

FIG. 2. Distribution of maximum pseudorapidity (η_{max}). Hadron level after colour reconnection with probability parameter R for all events and those satisfying the 'gap' definition (full line).

strong coupling $\alpha_s(0.5\,GeV)/\pi \approx 0.2$ at a 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 a detailed account of experimental conditions, such as acceptance and varying event vertex position. Selecting events with rapidity gaps similar to the H1 definition (i.e. no energy in $\eta_{max} < \eta < 6.6$ where $\eta_{max} < 3.2$) gives the full curve in Fig. 2, also in basic agreement with data [2].

Further features of our model are shown in Fig. 3, where the resulting distributions in momentum transfer $t = (p_p - p_R)^2$ 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 for the gap events, their distributions are similar to what is expected from diffractive models. This applies to the essentially exponential t-dependence, $1/M_X^2$ dependence and the M_R system being dominated by the proton.

The t-dependence in our model is intimately connected to the assumed distribution of primordial transverse momentum $k_\perp$ of partons in the proton, i.e. of the parton entering the hard scattering process. This transverse momentum is balanced by the proton remnant and, since momentum transfers in SCI are neglected, it is essentially the $p_\perp$ of the forward R-system, i.e. $p_{R,\perp}^2 = k_\perp^2$. Now, $t \approx -p_{R,\perp}^2$ in the case of interest, i.e. when the energy-momentum transfer from the beam proton to the X-system is small giving a very forward R-system. The primordial $k_\perp$ represents the non-perturbative Fermi motion in the proton and is therefore of the order $k_\perp \simeq 1\text{fm}^{-1}$ or a few hundred MeV as estimated from the uncertainty principle. This gives the width σ of the Gaussian distribution $\exp(-k_\perp^2/\sigma^2)dk_\perp^2$ which is normally assumed. Thus, one directly gets the exponential t-dependence $\exp(t/\sigma^2)dt$ with

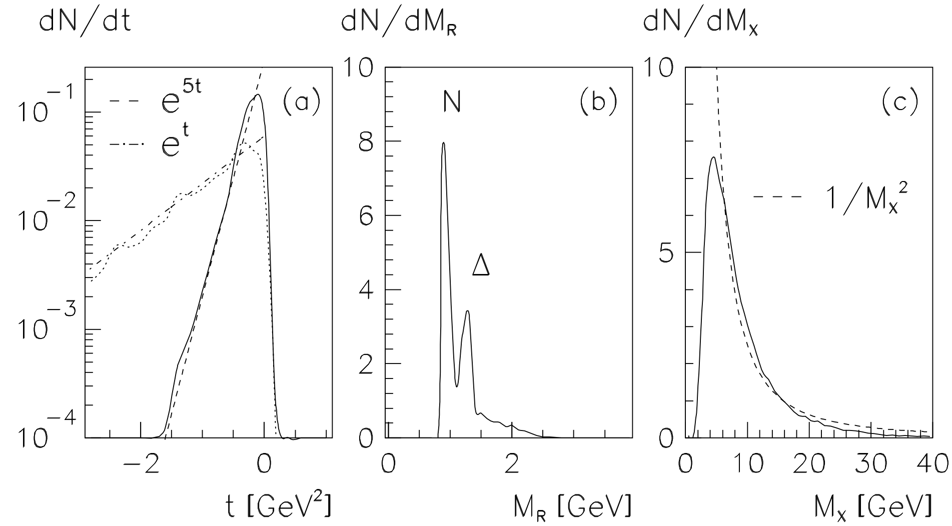

FIG. 3. Distributions (in arbitrary units) for the selected rapidity gap events, i.e. with no energy in $\eta_{max} < \eta < 6.6$ and $\eta_{max} < 3.2$: (a) squared momentum transfer t from incoming proton to remnant system R, for two widths $\sigma = 0.44$ (full) and 1 GeV (dotted) of the gaussian primordial $k_\perp$ distribution compared with exponential slopes $1/\sigma^2$; (b,c) invariant mass of the forward remnant system M_R and the produced central system M_X (cf. Fig. 1)

$\sigma^2 = 2\langle k_\perp^2 \rangle$ from the primordial $k_\perp^2$-distribution. As demonstrated in Fig. 3a, the input $k_\perp^2$-distribution is very well reproduced in the t-distribution of the Monte Carlo events.

The R-system is dominantly a single proton, as in a diffractive model based on pomeron exchange. However, there is also a substantial amount of Δ which would correspond to pion exchange in Regge phenomenology. The detailed composition of the R-system does in our case depend on the model [9] used for hadronizing a small-mass string system. This model is not constructed to give a detailed account of quantum numbers and masses in the resonance region, but rather a reasonable mean behaviour. This leaves some room for modifications that may change the detailed outcome, but still it should be possible to find distinguishing features in the R-system in comparison with Regge-based models.

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. Kinematically, larger M_X means a reduced gap and is therefore disfavored by the gap condition.

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. One must however keep in mind that the experimental conditions for selecting gap events, requiring a large gap that extends very forward in rapidity, gives a kinematical bias against large values of t and M_R. Given the different input concerning the formation of the forward system in our model and in pomeron models, it seems likely that observable differences should occur when varying the gap definition or observing the forward-moving R-system.

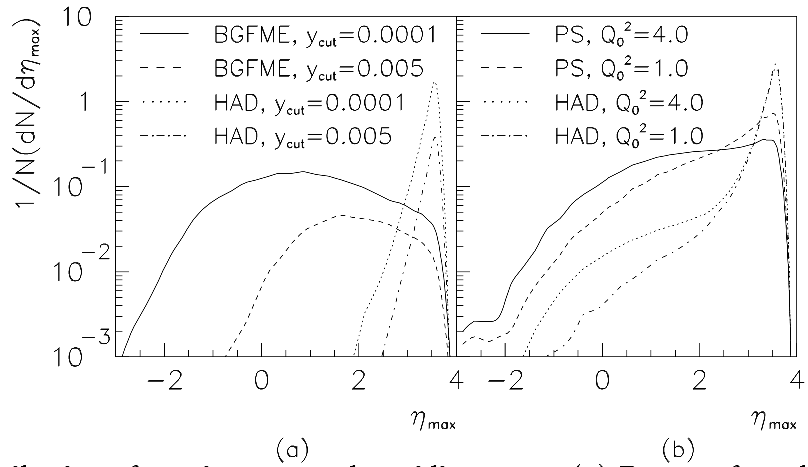

FIG. 4. Distribution of maximum pseudorapidity η_{max}. (a) Partons from boson-gluon-fusion matrix element (BGFME) with cut-off y_{cut}, and hadrons (HAD) after parton showers and string hadronization without SCI. (b) Parton level (PS) and hadron level (HAD), after SCI, for different initial state parton shower cut-off values Q_0^2.

The probability for gaps from SCI depends on the parton state used as starting configuration. Therefore, we must consider the influences from variations and uncertainties related to both the matrix elements and the higher order parton shower emissions. The maximum rapidity parton from the BGF matrix element (Fig. 4a) 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 [10], about 10 % are BGF events. The small $y_{cut} = 0.0001$ results in an automatic adjustment [8] of the cut-off such that the total (Born) cross section is saturated with $2+1$-jet events, giving $\sim 50\%$ BGF events. With the smaller y_{cut} the partons can emerge with a large rapidity gap relative to the spectator partons (at large η outside the scale of the figure and experimentally lost in the beam pipe). This gives a larger potential to produce gaps in the final state and $y_{cut} = 0.0001$ is therefore used as default in our model. Fig. 4a also demonstrates that normal parton showers and string hadronization give so large effects that those potential gaps does not survive in the absence of SCI.

Since parton showers and hadronization give so large effects the exact gap probability will depend on details of these. In particular, the cut-off Q_0^2 for the parton shower is rather important. Chosing a value close the hadronic mass scale $\sim 1\,GeV^2$ tends to produce too much radiation at large rapidity such that the gaps are partly destroyed (Fig. 4b). A value of $4\,GeV^2$ for the limit of pQCD, as in many parton density parametrizations, reduces such emissions and thereby larger gaps can arise after SCI. This has been taken as the default value in our model.

In this context one should note that the conventional leading $\log Q^2$ evolution need not be correct when applied to the treatment of exclusive parton final states in a parton shower. It is derived [11] for not-too-small x and only for the inclusive case, i.e. for the evolution of the structure function. It therefore 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 can occur in the emission chain. Some events may therefore have less parton radiation than estimated in this way and these would favour the occurence of rapidity gaps.

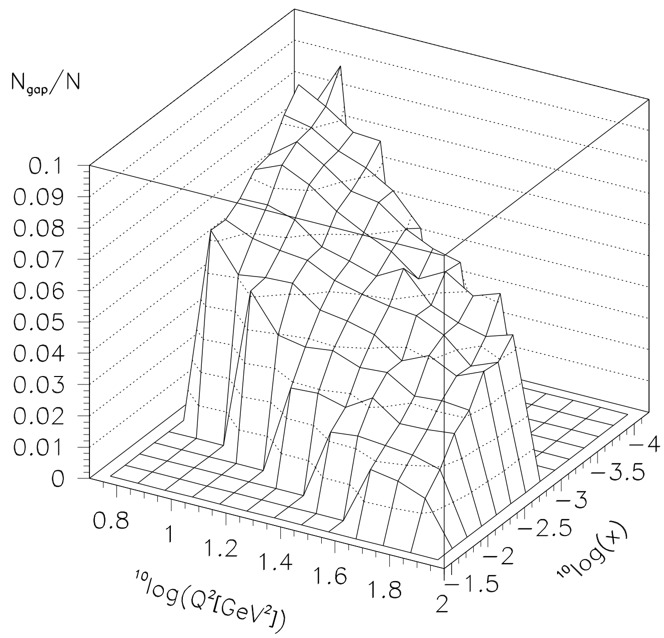

FIG. 5. Ratio of rapidity gap events, i.e. with no energy in $\eta_{max} < \eta < 6.6$ and $\eta_{max} < 3.2$, to all DIS events as function of x and Q^2.

Since the soft colour interactions in our model are factorized with respect to the hard interaction, one may expect that the rate of gap events is essentially independent of the DIS kinematical variables x and Q^2. This is, however, not quite the case as shown in Fig. 5. The variation in x, at fixed Q^2 is significant. A smaller part of the effect is from the increase of gluon induced hard scatterings as x decreases. However, most of it is a purely kinematic effect due to the gap definition. With increasing x, i.e. harder incoming parton, the hard scattering system moves forward and decreases thereby the rapidity distance between those partons and the proton remnant system. This reduces the possibility for a large gap to occur.

The Q^2 dependence is more due to the model itself. With increasing Q^2 the maximum virtuality in the initial state parton shower increases and thereby the amount of radiation. Since the initial radiation tends to be along the incoming parton, i.e. the proton beam, this means more partons at rapidities between the current and the spectator and thereby a tendency to spoil the gap. This gives a decrease in the relative rate of gap events. The exact numerical values will here depend on the details of the parton shower which are, as discussed, not well settled.

Although the rate of gap events in the data [1,2] is, within errors, essentially independent of Q^2 for fixed x, there are indications of some variations of the same kind as in our model. A closer comparison with the coming higher statistics data will therefore be interesting.

Another testing ground for the model may be provided by data on $F_2^D(\beta, Q^2)$ [2]. This quantity can, in pomeron-based models, be interpreted as the pomeron F_2 structure function [12], giving the density of partons with momentum fraction β in the pomeron. Applying conventional QCD evolution of these partons in the pomeron should then give the Q^2-dependence and explicit such calculations have been performed [12,13]. Having no pomeron in our model, one should instead consider the evolution of partons with momentum fraction x in the proton. Although there is then no direct physical interpretation of F_2^D, it can still be extracted from the model and compared with data.

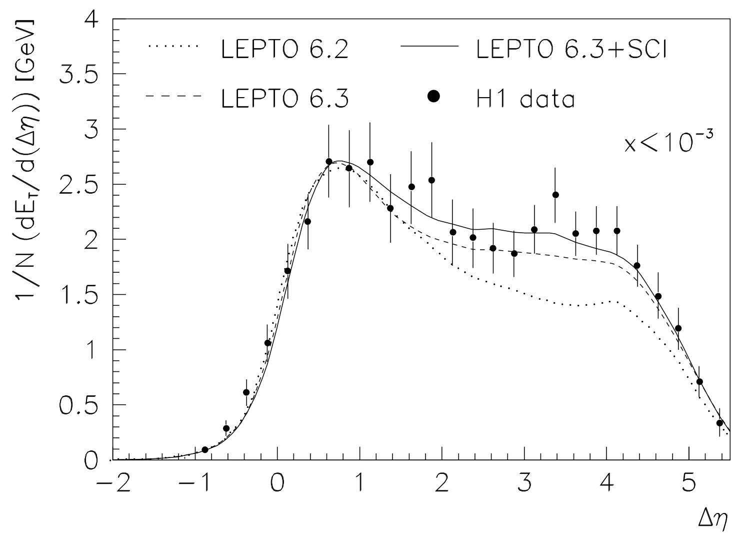

FIG. 6. Transverse energy flow versus $\Delta\eta = \eta - \eta_{q/QPM}$, i.e. lab pseudorapidity relative to the current direction in QPM kinematics, for events with $x < 10^{-3}$. The curves are from the earlier Monte Carlo model (6.2), with improved parton shower and sea quark treatment (6.3) and, in addition, with soft colour interactions (6.3+SCI).

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. 6, the E_T-flow data [14] can be well described by our new model. The soft colour interactions generates not only gap events, but also larger fluctuations in general. In particular, configurations may arise where the string goes 'back and forth' and thereby produce more energy per unit rapidity. The effect is demonstrated by the difference between the dashed and full curves in Fig. 6.

Of relevance for this observable, as well as the gap events, is also the modelling of the non-perturbative proton remnant system, i.e. the proton 'minus' the parton entering the hard scattering process. In case a valence quark is removed the remainder is a diquark which is taken as a colour anti-triplet at the end of a string, to which Lund model hadronization is applied. However, if a sea quark is removed the remainder is more complex with the valence quarks plus the partner anti-quark from the sea to conserve quantum numbers. In this study, we have improved the Monte Carlo model by assigning the removed quark to be a valence or sea quark and, in case of a sea quark, given its partner in the remnant some dynamics.

Thus, the interacting quark is taken as a valence or sea quark from the relative sizes of the corresponding parton distributions $q_{val}(x_1, Q_1^2)$ and $q_{sea}(x_1, Q_1^2)$, where x_1 is the known momentum fraction of the quark 'leaving' the proton and Q_1^2 is the relevant scale (typically the cutoff Q_0^2 of the initial state parton shower). In case of a sea quark, the left-over partner is given a longitudinal momentum fraction from the corresponding parton momentum distribution or, with similar results, from the Altarelli-Parisi splitting function $P(g \to q\bar{q})$. In the latter case, the transverse momentum follows from the kinematics once the partner mass has been fixed. This parton and the three valence quarks, which are split into a quark and a diquark in the conventional way [8], form two colour singlet systems (strings) together with the scattered quark (and any emitted gluons). This two-string configuration for sea-quark initiated processes provides a desirable continuity to the two-string gluon-induced BGF events, thereby reducing the dependence on the value of the matrix element cut-off y_{cut}. Depending on the partner sea quark momentum, the corresponding string will extend more or less into the central region in rapidity. The hadronization of this extra string will thereby give another contribution to the forward energy flow, as illustrated by the difference between the dotted and dashed lines in Fig. 6.

If this new attempt to understand the rapidity gap phenomenon turns out successful in detailed comparison with data, it will circumvent some problems in the pomeron-based approach. In particular those associated with the concept of a preformed exchanged object. This object cannot be a real particle or state, since it has a negative mass square t. It could be a virtual exchange corresponding to some real state, such as a glueball, but this is presently unclear (although a recent glueball candidate [15] fits on the pomeron trajectory). The interpretation of factorization in Regge phenomenology in terms of an emission of a pomeron given by a pomeron flux and a pomeron-particle interaction cross section also has some problems. Since it is only their product that is experimentally observable one cannot, without further assumptions, define the absolute normalisation of this flux and cross section unambigously [5]. This also gives a normalization ambiguity for the parton densities of the pomeron which is reflected in the problem of whether they fulfill a momentum sum rule or not. Leaving the concept of a preformed object and instead considering [16] a process with interactions with the proton both before and after the hard scattering (taking place at a short space-time scale) may avoid these problems, as in our model. One may ask whether the soft colour interactions introduced here is essentially a model for the pomeron. This should not be the case as long as no pomeron or Regge dynamics is introduced in the model. It remains to be seen if the model can stand the test against data without any such extra assumptions. In this sense, it is important to consider typical diffractive characteristics, e.g. the properties of the forward R-system, in more detailed comparisons with data.

Finally, we note that our model is similar in spirit to the one of Buchmüller and Hebeker [17], which was developed independently and in parallel with ours. Their model only considers the matrix element part, where the whole DIS cross section is taken to be saturated by BGF, and introduces a statistical probability that the $q\bar{q}$ pair is changed from a colour octet into a colour singlet state. In our study, the influence of higher order parton emissions are examined, a model for the colour exchange is introduced and hadronization is taken into account. Having formulated our model in terms of a Monte Carlo generator that simulates the complete final state, more detailed comparisons with data can be made.

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 in addition to the perturbative ones. 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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REFERENCES

[1] ZEUS Coll., Phys. Lett. B315 (1993) 481; DESY 95-093

[2] H1 Collaboration, Nucl. Phys. B429 (1994) 477; Phys. Lett. B348 (1995) 681

[3] G. Ingelman, P.E. Schlein, Phys. Lett. B152 (1985) 256

[4] G. Ingelman, J. Phys. G: Nucl. Part. Phys. 19 (1993) 1633

[5] P.V. Landshoff, Introduction to the Pomeron Structure Function, hep-ph/9505254, presented at workshop on 'DIS and QCD', Paris, April 1995

[6] A. Edin, G. Ingelman, J. Rathsman, DESY 95-145, presented at workshop on 'DIS and QCD', Paris, April 1995

[7] B. Andersson et al., Phys. Rep. 97 (1983) 31

[8] G. Ingelman, proc. 'Physics at HERA', DESY 1991, p. 1366

[9] T. Sjöstrand, Comp. Phys. Comm. 82 (1994) 74

[10] G. Ingelman, J. Rathsman, Z. Phys. C63 (1994) 589

[11] V.N. Gribov, I.N. Lipatov, Sov. J. Nucl. Phys. 15 (1972) 438
G. Altarelli, G. Parisi, Nucl. Phys. B126 (1977) 298

[12] G. Ingelman, K. Prytz, Z. Phys. C58 (1993) 285

[13] H.G. Kohrs, Direct and Resolved Pomeron, hep-ph/9507208, presented at workshop on 'DIS and QCD', Paris, April 1995
A. Capella et al., LPTHE-ORSAY-95-33, hep-ph/9506454
K. Golec-Biernat, J. Kwiecinski, Phys. Lett. B353 (1995) 329
T. Gehrmann, W.J. Stirling, Durham preprint DTP/95/26

[14] H1 Collaboration, I. Abt et al., Z. Phys. C63 (1994) 377

[15] WA91 Collaboration, Phys. Lett. B324 (1994) 509, *ibid.* B353 (1995) 589

[16] A. Berera, D.E. Soper, Phys. Rev. D50 (1994) 4328

[17] W. Buchmüller, A. Hebecker, Phys. Lett. B355 (1995) 573, presented at workshop on 'DIS and QCD', Paris, April 1995