Rapidity gaps at HERA and the Tevatron from soft colour exchanges†

Rikard Enberg, Gunnar Ingelman and Nicusor Timneanu
High Energy Physics, Uppsala University
Box 535, S-751 21 Uppsala, Sweden, enberg@tsl.uu.se

Abstract. Models based on soft colour exchanges to rearrange colour strings in the final state provide a general framework for both diffractive and non-diffractive events in ep and hadron-hadron collisions. We study two such models and find that they can reproduce rapidity gap data from both HERA and the Tevatron. We also discuss the influence of parton cascades and multiple interactions on the results.

The rapidity gap events observed at HERA have traditionally been explained by Regge-inspired models based on hard scattering of a parton in a pomeron, emitted from one of the protons [1]. These models work well in reproducing HERA data, but in recent years rapidity gap events have also been observed at the Tevatron [2–8]. These data cannot be reproduced using a pomeron model with parametrizations of the pomeron structure function from HERA data [7,9]. This may indicate that the pomeron approach is not universal, e.g. that the pomeron flux factorization is not so simple. It is also clear that perturbative QCD cannot fully describe the formation of rapidity gaps, since they involve the soft part of the event, with a long space-time scale.

A different approach has been developed [10,11], where the non-perturbative dynamics is modelled with soft colour exchanges, leading to variations in the topology of the confining colour field, e.g. described by Lund strings [12]. There are two models, which are similar in spirit but different in details: the Soft Colour Interaction (SCI) model [10] and the Generalized Area Law (GAL) model [11]. In the former, the partons emerging from the hard scattering are assumed to interact softly with the colour field of the proton, whereas in the latter, there are soft colour exchanges between overlapping strings. In both cases, the colour interactions lead to rearrangements of the colour charges and thereby the string topology. Given the softness of these interactions, changes in momenta are neglected.

The rearrangements, or reconnections, of the strings may lead to phenomena such as rapidity gaps, leading protons or leading neutrons. Another effect is that a c ¯c pair may turn into a colour singlet and form a charmonium state [13].

The initial colour order of the partons in the final state is given by the planar approximation in perturbative QCD, but this colour order may now be changed by the soft colour exchanges. In figure 1a, we show how this can give rise to diffractive W production in pp collisions at the Tevatron. The upper diagram shows the standard QCD string configuration, with strings spanning the entire rapidity region. The lower

† Presented by R. Enberg at UK Phenomenology Workshop on Collider Physics, Durham, England, September 1999
Rapidity gaps from soft colour exchanges

\[ \text{Figure 1.} \ (a) W \text{ production in } \bar{p}p \text{ with string topology before and after colour rearrangement. Comparison of the SCI and GAL models to (b) the diffractive structure function } F_2^{D(3)} \text{ as measured by H1 [16] (plot from [17]), and (c) the ratio of diffractive to total cross-section for } W \text{ production [2] and di-jet production [3] as measured by CDF.} \]

Diagram shows the situation after a reconnection of the strings, where there is a region in rapidity not covered by a string, such that a rapidity gap arises after hadronization. It is an important feature of the models that there is no sharp distinction between diffractive and non-diffractive events, but a smooth transition between the two types of events.

The two models have been implemented in the Monte Carlo event generators LEPTO [14] for DIS and PYTHIA [15] for \( \bar{p}p \)-collisions. This makes it possible to take an experimental approach and classify events as diffractive or non-diffractive depending on the characteristics of the final state. The models are introduced in the programs as a loop over all pairs of partons (SCI) or strings (GAL) and each pair is allowed to exchange colour with a certain probability given by the free parameter \( R \), which cannot be calculated in perturbation theory. In the SCI model, \( R \) is taken as a constant and fitted to HERA data [10]. In the GAL model, \( R = R_0 [1 - \exp(-b \Delta A)] \) depends on the change \( \Delta A \) that the string rearrangement introduces in the generalized ‘area’ swept by the strings in energy-momentum space [11]. \( R_0 \) is a free parameter, simultaneously fitted to HERA and LEP data.

Both the SCI model and the GAL model give good descriptions of diffractive HERA data, e.g. the diffractive structure function in figure 1b, but also of more detailed properties of the diffractive X-system [17, 10, 11]. However, the description of inclusive final states is not as good for the SCI model, which gives too many soft particles, whereas the GAL model clearly improves this situation [17]. The reason is that the GAL model suppresses strings associated with a large area (‘long strings’) while the SCI models allows reconnections giving long zig-zag-shaped strings.

Diffractive in \( \bar{p}p \) collisions at the Tevatron offers a new testing ground for these models. We have applied both the SCI and the GAL models to \( \bar{p}p \) collisions [18] in order to investigate \( W \) and di-jet production in association with a rapidity gap, and also central di-jet production with two rapidity gaps.

Both models reproduce well the rates observed at the Tevatron for production of diffractive \( W \) and diffractive di-jets when the \( R \)-value obtained from HERA data is used (see figure 1c and table 1). The double gap fraction, i.e. the fraction of events with two gaps, conventionally associated with double pomeron exchange, also comes out in decent agreement with data. This should be contrasted to the pomeron model, which, when tuned to HERA data, overestimates the rates of diffractive di-jets by a factor 6 for single gap events and 275 for double gap events [7].

In hadron-hadron collisions it is also important to consider the underlying event, since additional soft activity may spoil the rapidity gaps. We therefore used the model for multiple interactions [19] present in PYTHIA, where the underlying event activity is described by additional parton-parton scatterings with a minimum transverse
Table 1. Experimental rates (diffractive/inclusive) measured at the Tevatron and the results obtained from the SCI and GAL models for these rates.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expt</th>
<th>√s</th>
<th>Ref.</th>
<th>Rate (%)</th>
<th>SCI</th>
<th>GAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>W - gap CDF</td>
<td>1800</td>
<td>[2]</td>
<td></td>
<td>1.15 ± 0.55</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>jj - gap CDF</td>
<td>1800</td>
<td>[3]</td>
<td></td>
<td>0.75 ± 0.10</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>jj - gap DØ</td>
<td>1800</td>
<td>[4]</td>
<td></td>
<td>0.76 ± 0.08</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>jj - gap DØ</td>
<td>630</td>
<td>[4]</td>
<td></td>
<td>1.11 ± 0.23</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>gap - jj -gap</td>
<td>CDF</td>
<td>1800</td>
<td>[5]</td>
<td>0.26 ± 0.06</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>gap - jj -gap</td>
<td>DØ</td>
<td>1800</td>
<td>[6]</td>
<td>(not published)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

a Ratio of 2-gap events to 1-gap events.
b We have not yet obtained a rate for the GAL model.

momentum \( P_{\text{min}} \). However, the SCI model also contributes to the soft underlying event. To avoid ‘double counting’, we decrease the amount of multiple interactions by increasing the free parameter \( P_{\text{min}} \) by about 500 MeV to 2.5 GeV, so that the net activity in the event will be the same. Having no multiple interactions (no MI in figure 1c) gives a higher gap rate due to an unrealistically low event activity. Because of the suppression of ‘long’ strings, the GAL model contributes less to the underlying event and \( P_{\text{min}} \approx 2.0 \text{ GeV} \) can be used. Pythia used with the SCI/GAL models results in essentially the same jet profiles, rapidity plateaux, and particle multiplicities as default Pythia.

Another phenomenon that has been observed is central rapidity gaps between jets, so that there is a hard momentum transfer across the gap. We find [18] that the gap rates obtained using the GAL model as above are in agreement with the Tevatron data, but there are uncertainties related to multiple interactions. The SCI model does give such events too, but the rate is too low.

A potential problem is that the rate of gap events also depends on the amount of perturbative emissions. It is known that the DGLAP evolution scheme does not give enough perturbative gluon emission in the forward region of small-\( x \) DIS events at HERA [20]. This may make SCI and DGLAP in Lepto overestimate the gap rate. Using SCI or similar models [21] in Ariadne [22], which gives a better description of hard emissions in the forward region, gives a too low gap rate unless the cut-off parameter in the cascade is increased. Similarly, the \( R \) parameter in SCI and GAL can be increased to give a larger gap rate in case of more perturbative emissions.

In this context, one should realize that these cascade models are not very well founded theoretically. DGLAP is derived in perturbative QCD for the inclusive case, whereas the cascade in Ariadne is given by a dipole approximation not based on Feynman diagrams. Although one may expect that they give fair descriptions of the mean behaviour, there is no guarantee that they account for the fluctuations in the perturbative QCD emissions. Downwards fluctuations in the number of gluons are important for rapidity gap formation. It is therefore premature to draw too strong conclusions about this problem, which needs further investigations. To this end, we have during this workshop started to implement the SCI and GAL models in the Rapgap Monte Carlo [23] which uses a model for resolved photons to describe forward parton emissions.

In conclusion, the SCI and GAL models can give satisfactory descriptions of rapidity gap events in both \( ep \) and \( pp \) collisions. They also reproduce many features of non-gap events, such that a unified description of both diffractive and non-diffractive
Rapidity gaps from soft colour exchanges

interactions are obtained. Although these models are simple and leave some problems unsolved, they may represent a new way to improve our understanding of non-perturbative QCD dynamics.

Acknowledgments

We thank Anders Edin, Leif Lönblad and Johan Rathsman for helpful discussions.

References

[8] Cox B E, Goulianos K, Lönblad L and Whitmore J J these proceedings
[23] Lönblad L 1996 Z. Phys. C 70 107