MODELING DIFFRACTIVE FINAL STATES*

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(Received July 1, 2002)

I will discuss some aspects of modeling diffractive final states with event generators. In the first part of the talk I will discuss multiple scatterings in hard diffraction in hadron collisions and its effects on gap survival and hadronization corrections. In the second part I will argue that the study of the 'pomeron remnant' in hard diffraction at HERA may be the best way of distinguishing resolved pomeron models from dipole models and soft colour interaction models.

PACS numbers: 12.38.Cy, 13.85.Hd

1. Introduction

Although it has been almost a decade since large rapidity gap events were first observed in DIS at HERA [1, 2], there is still no consensus about what the underlying mechanism may be. The resolved factorized pomeron model [3], which actually predicted the effect, has been followed by several other models such as the Soft Colour Interaction (SCI) model [4], the saturation model [5] and the two-gluon exchange model in [6, 7]. Most models are able to describe semi-inclusive measurements such as the diffractive structure function, F_2^{D3}, but to really check which models actually describes the underlying physics it is necessary to investigate if they can reproduce the measured features of the diffractive final states. Furthermore it is important that the models also can describe the hard diffraction observed at the Tevatron (see *e.g.* [8–10]) if we believe that these gaps are caused by the same mechanism.

To investigate hadronic final states we need good event generators implementing the models to get a handle on effects of QCD evolution and hadronization of perturbatively produced partons. Such generators exist for most models for DIS diffraction, *e.g.* Rapgap [11], Pompyt [12],

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.

Pomwig [13], Lepto [14] and Satrap [15], and it is clear several models have great problems to describe *e.g.* di-jet production [16]. I will comment on some of these models in Section 3.

For hard diffraction in hadron–hadron collisions, it is also important to use event generators to carefully take into account the effects of evolution and hadronization of partons. Here even semi-inclusive quantities such as gap fractions may involve jet reconstruction, and the naive assumption that hadronization corrections cancels in the ratio of gap- to non-gap-events is not valid. In hadronic collisions it is also important that the so-called gap-survival probabilities are taken into account. This will be discussed in the following.

2. Gap survival and multiple interactions

Looking at different ways of cutting p–p forward scattering ladder diagrams, it is easy to see that rapidity gap events are closely related to multiple scattering (or multiple interaction — MI) events. In particular we realize that if a potential gap event is accompanied by an additional scattering, the gap will be destroyed. Hence, the factorization properties of rapidity gaps observed in DIS, where MI's are heavily suppressed due to the large Q^2, is not present in p–p. What may save the day is if secondary scatterings to a good approximation are independent of whether the primary, or *trigger* interaction is a normal inelastic or a (hard-) diffractive one. It should therefore be possible to take the pomeron flux and parton densities as determined at HERA and apply them to p–p collisions, introducing a universal gap-survival probability given by the probability of there being no additional scatterings beside the diffractive one.

Hence it is important to be able to model the MI's properly in order to understand the rapidity-gap events at *e.g.* the Tevatron. Here I will only briefly discuss the MI model implemented in the Pythia [17, 18] event generator. It should be noted that Pythia itself does not generate hard diffraction events, but as will be shown, the MI model is rather insensitive to the details of the primary scattering, and therefore we can use it to determine a process-independent probability of there being no additional scatterings, leading us to a universal gap-survival probability.

MI is an inherently soft phenomena and is therefore very difficult to model. The basic strategy in Pythia is to look at the eikonalization of the (mini-) jet cross-section and to use partonic 2→2 matrix elements (ME's) down to very low scales, effectively modeling also soft interactions with perturbative-like scatterings. To accomplish this, the 2→2 ME's, and also the strong coupling, are regularized with a small scale, $p_{\perp 0}$ so that

$$\frac{d\hat{\sigma}}{dp_\perp^2} \to \frac{d\hat{\sigma}}{dp_\perp^2} \times \frac{p_\perp^4}{(p_{\perp 0}^2 + p_\perp^2)^2}, \quad \alpha_{\mathrm{s}}(p_\perp^2) \to \alpha_{\mathrm{s}}(p_{\perp 0}^2 + p_\perp^2)\,. \tag{1}$$

In addition, the partonic flux is impact-parameter dependent, so that *e.g.* the cross-section for jet production is eikonalized according to

$$\frac{dP_{\text{hardest}}(b,E_\perp)}{d^2b\,dE_\perp} \propto e(b)\frac{d\sigma(E_\perp)}{dE_\perp}\exp\left\{-\int_{E_\perp} e(b)\frac{d\sigma(E'_\perp)}{dE'_\perp}dE'_\perp\right\}, \qquad (2)$$

where the overlap function $e(b)$ is obtained assuming a double-Gaussian matter distribution in the proton. The exponent is simply interpreted as the probability of there being no scattering above the hardest one at $E_\perp$. The scale $p_{\perp 0}$ needs to be adjusted so that the total inelastic cross-section is reproduced and will in general be dependent on the total energy.

For a single-diffractive (SD) jet event we would then get

$$\frac{dP^{\text{SD}}_{\text{hardest}}(b,E_\perp,x_{\mathbb{P}})}{d^2b\,dE_\perp\,dx_{\mathbb{P}}} \;\propto\; e(b)\frac{d\sigma^{\text{SD}}(E_\perp,x_{\mathbb{P}})}{dE_\perp\,dx_{\mathbb{P}}}\exp\left\{-\int_{E_\perp} e(b)\frac{d\sigma(E'_\perp)}{dE'_\perp}dE'_\perp\right\}$$
$$\times\exp\left\{-\int^{E_\perp} e(b)\frac{d\sigma(E'_\perp)}{dE'_\perp}dE'_\perp\right\}, \qquad (3)$$

where the $x_{\mathbb{P}}$-dependence naturally does not appear in the exponents, which corresponds to the probability of there being no scattering of any kind above $E_\perp$ and no additional scatterings below $E_\perp$ respectively. The two exponents together with the overlap factor can now simply be integrated over b and will give a gap survival probability. It is clear that the MI model in Pythia is just a model, but the fact is that it can fairly well reproduce data on *e.g.* the jet pedestal effect from the Tevatron [19] and other hadron colliders.

The MI's in Pythia are to a good approximation universal as long as the x_1, x_2 (or $x_{\mathbb{P}}$) are small (otherwise there is less energy left for MI) and as long as the (hardest) jet-$E_\perp$ are not to small, (otherwise we may be biased towards few MI's).

In addition there is a strong dependence on the total energy due to the strong rise of the gluon density at small x. The gap-survival probabilities predicted for the Tevatron from the default setting of MI's in Pythia are $\approx 16\%$ at 1800 GeV and $\approx 20\%$ at 630 GeV [20].

We note that MI's are responsible for the jet pedestal effect and the *underlying event* and that triggering on a rapidity gap means *vetoing* MI's. This means that the jet pedestal is different in gap events and in non-gap events, which must be taken into account when doing jet-energy corrections, especially when dealing with low-$E_\perp$ jets.

3. Soft Colour Interactions and similar models

One model which actually is able to generate rapidity gaps in hadronic collisions, including gap-survival probabilities modeled by MI's in Pythia, is the Soft Colour Interaction (SCI) model [4], but as I will argue here, it is highly questionable if this model has anything thing to do with reality. The basic idea in SCI is that the perturbative stage in *e.g.* DIS is the same irrespective of whether it is a rapidity-gap event or not. The process is modeled in the Lepto program by the standard backward evolution parton shower (as in figure 1(a)) followed by exchange of soft gluons which may or may not result in net colour singlet exchange (as in figure 1(b)). The colour exchanges may be completely random or, as in the so-called generalized area law model [21], biased towards exchanges which shortens the total string length.

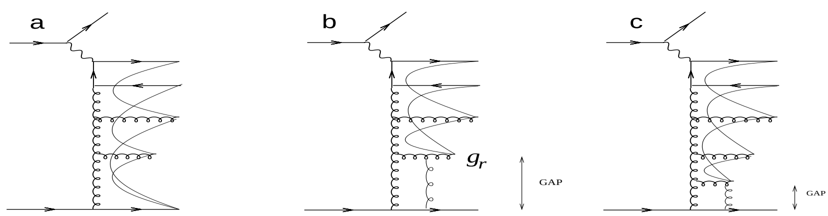

Fig. 1. The colour flow in the SCI model. (a) is a normal DIS event generated by Lepto, (b) is the same event after colour rearrangement and (c) shows the effect of an additional gluon emission.

The main problem with this model is that it is very sensitive to the rate and distribution of the emissions of gluons in the forward region, *i.e.* in the direction of the proton. Clearly if an additional gluon is radiated close to the proton as in as in figure 1(c), the size of a potential gap is decreased. Hence, for the model to make sense, it is important to show that the model is able to describe properly the emission of forward gluons. But it is well known that the parton shower in Lepto completely fails to describe *e.g.* forward jet production in DIS at HERA, which is enough to seriously doubt the physical relevance of the model. In fact, a similar colour exchange model in the Ariadne [22] program, which does describe forward jet production, completely fails to reproduce both the rate and distribution of rapidity gap events in DIS [23].

Still, the SCI model has been very successful in reproducing the rate rapidity gap events both from HERA and the Tevatron. To completely rule out the model we must again look at the description of the final state. The main difference between the SCI and resolved pomeron models is the description of the pomeron remnant. Although the exchanged gluons in figure 1(b) may be both soft, the last emitted gluon, g_r, is perturbative. In a resolved pomeron model, g_r corresponds to the pomeron remnant, which clearly is a soft object. Although the pomeron remnant has not been studied in detail at HERA, there are several studies of the hadronic final state in diffractive events, and it is clear that the SCI model gives a very poor description of *e.g.* diffractive di-jets [16], while the resolved pomeron model satisfactorily reproduces data.

It should be noted that the so-called dipole [24] and saturation [5] models are very similar to the SCI model, in the respect that they rely on the perturbative evolution being the same in diffractive and non-diffractive events. The difference is that the dipole and saturation models look at the evolution of the $q\bar{q}$ state produced by the virtual photon in the rest system of the proton. This state then interacts with the proton by exchanging soft gluons which may or may not result in a net colour singlet exchange and hence a rapidity gap. Although the exchanged gluons may be soft, the gluons in the evolved $q\bar{q}$ state are produced perturbatively and will result in a *hard* pomeron remnant, just as in the SCI model.

Also for the dipole and saturation models it is important that the description of forward parton emission is well described, since also in those cases the gaps would be destroyed by additional gluon emission close to the proton direction. And since these models typically only consider the emission of *one* extra gluon, it is very questionable if there is any physical relevance of the fact that they get the rate of rapidity gaps right. In fact also these models fail to satisfactorily describe final-state properties of gap events at HERA.

The so-called BJLW model [6,7,15] is similar to the dipole and saturation models, but includes BFKL resummation for the evolution of the $q\bar{q}$ state, which should help in the description of forward jet-production and thus give a more theoretically safe description of the rate of rapidity gaps. In fact it also does a good job in describing the diffractive final states. Also the description of the pomeron remnant is reasonable and similar to the resolved pomeron model, although the former is a perturbative object while the latter is soft. Clearly a more detailed investigation of the hadronic final state in general and of the pomeron remnant in particular is needed to separate these models.

4. Conclusions

To really understand the physical mechanism behind rapidity gaps it is not enough to just look at semi-inclusive quantities such as F_2^{D3} and gap fractions, which can be described by a wide range of models. Instead we must study the details hadronic final state, and in particular I suggest to closely study the *edge* of the rapidity gap to get a handle on the nature of the equivalent of the pomeron remnant. To do this we need good event generators implementing the different models.

In particular for hadronic collisions it is important to use event generators, since there the gap fractions typically involve jets which are sensitive to hadronization effects and the so-called underlying event. Since there are differences both in colour topology and in the underlying event for gap and non-gap events these effects do not cancel when taking ratios. In hadron collisions it is also important to model the gap-survival probability and I have argued that multiple interactions models are a good tool for this.

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