Is BFKL ruled out by the Tevatron gaps between jets data?

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We have performed a detailed phenomenological investigation of the hard colour singlet exchange process observed at the Tevatron in events that have a large rapidity gap between outgoing jets. We include the effects of multiple interactions to obtain a prediction for the gap survival factor. Comparing the data on the fraction of gap events with the prediction from BFKL pomeron exchange we find agreement provided that a constant value of α_s is used in the BFKL calculation. Moreover, the value of α_s is in line with that extracted from measurements made at HERA.

1. Introduction

Events with large rapidity gaps in the hadronic final state and a large momentum transfer across the gap, characterised by the presence of a hard jet on each side of the gap, have been observed in both $p\bar{p}$ collisions at the Tevatron [1–4] and in γp collisions at HERA [5,6]. Such events are unexpected in standard Regge phenomenology since the cross section is predicted to fall as $\sim s^{-\alpha|t|}$, where $\alpha \simeq 0.25$ GeV^{-2}, whilst events with $|t| > 1000$ GeV^2 are routinely observed at the Tevatron. Clearly some other explanation must be sought. Uniquely in diffractive physics, high-t events are amenable to the use of perturbative QCD since the gap producing mechanism is squeezed to small distances [7]. Such calculations have been carried out within the leading logarithmic approximation of BFKL [8] by Mueller and Tang [9], and it is the aim of this talk to present comparisons of these calculations with the latest data from the Tevatron. The situation is greatly complicated by the possibility that rapidity gaps formed by whatever process can be destroyed by multiple interactions between spectator partons in the colliding hadrons. Detailed comparisons made and conclusions drawn from any dynamic model of high-t rapidity gap formation must therefore include a careful treatment of such physics. In this analysis, we use a model implemented in the PYTHIA Monte Carlo generator to simulate the effects of multi-parton interactions.

2. DØ data versus the BFKL pomeron

The analysis presented here was stimulated to some extent by the recent DØ measurements [2] of the fraction of dijet events containing a large rapidity gap as a function of E_{T2}, the E_T of the second hardest jet, and the rapidity difference between the two leading jets, $\Delta\eta$. The DØ results are shown in figure 1. Jets are found using a cone algorithm [10,11] with cone radius 0.7 and the OVLIM parameter set to 0.5. The inclusive dijet sample is defined by the following cuts:

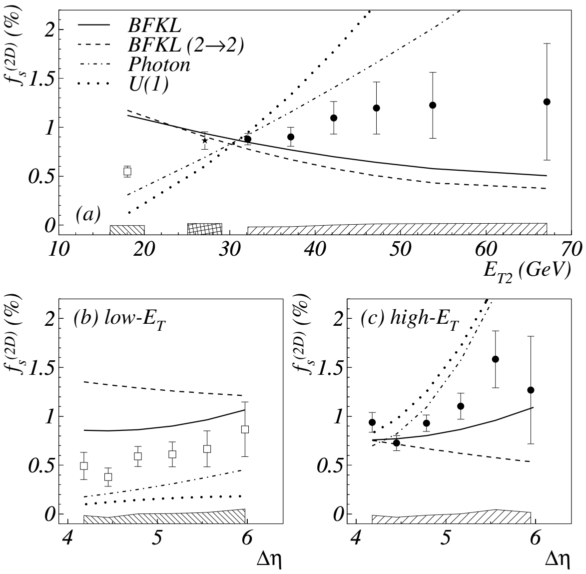

Figure 1. DØ data compared with a BFKL calculation. Plot from [2].

- $|\eta_1|, |\eta_2| > 1.9$, i.e. jets are forward or backward
- $\eta_1\eta_2 < 0$, i.e. opposite side jets
- $E_{T2} > 15$ GeV
- $\Delta\eta > 4$, i.e. jets are far apart in rapidity.

The sub-sample of gap events is obtained by employing the further cut that there be no particles emitted in the central region $|\eta| < 1$ with energy greater than 300 MeV. The BFKL curve is clearly ruled out by the data. The DØ BFKL curves are based on the calculation of Mueller and Tang implemented into the standard HERWIG 5.9 release [12,22]. In particular, the asymptotic cross-section of [9] is used; in the limit $y \equiv \Delta\eta \gg 1$,

$$\frac{d\sigma(qq \to qq)}{dt} \approx (C_F \alpha_s)^4 \frac{2\pi^3}{t^2} \frac{\exp(2\omega_0 y)}{(7\alpha_s C_A \zeta(3) y)^3} \qquad (1)$$

where $\omega_0 = \omega(0) = C_A(4\ln 2/\pi)\alpha_s$. The α_s^4 in the pre-factor runs with $-t$ according to the two-loop beta function, $\omega_0 = 0.3$ and the α_s in the denominator $= 0.25$. The falling of the BFKL curve with increasing E_{T2} is driven by the running of the coupling in the pre-factor since the gap fraction goes like $\sim \alpha_s^4/\alpha_s^2$.

3. Key issues

In this analysis, we choose somewhat different parameters. We also use the full Mueller Tang calculation without the asymptotic approximation. This is also available in HERWIG 5.9 [23] and is available from the authors. We choose to fix $\alpha_s = 0.17$. To leading logarithmic accuracy α_s is simply an unknown parameter. Higher order corrections will indeed cause the coupling to run, however it is not clear how this should be done in a consistent way. In this paper we restrict ourselves to the leading logarithmic approximation and treat the coupling as a free parameter. Moreover, we are guided by recent HERA data on the double dissociation process [13] which can be described by the leading logarithmic BFKL formalism with $\alpha_s = 0.17$. We also note that a fixed coupling constant was needed in order to explain the high-t data on $p\bar{p}$ elastic scattering via three gluon exchange [14]. Furthermore, NLO corrections suggest a fixed value for the leading eigenvalue of the BFKL equation, $\omega(0)$, [15] which in turn suggests the use of a fixed coupling in the LLA kernel.

Underlying events and gap survival

As mentioned above, it is critical in any estimate of gap formation rates to take into account the possibility that gaps can be destroyed by secondary scatters, which may be perturbative or non-perturbative, between spectator partons in the colliding hadrons. Several models are available [16–18], but it would be fair to say that all are as yet in a early stage of development and are not tuned to $p\bar{p}$ data. We choose the model

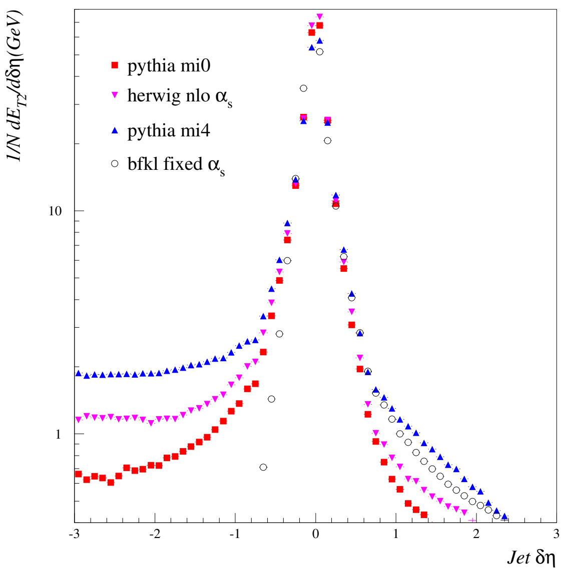

Figure 2. Jet η profiles

as implemented in PYTHIA 6.127 [17]. Here the probability to have several parton-parton interactions in the same collision is modelled using perturbative QCD. The probability for additional interactions is not fixed but varies according to an impact-parameter picture, where central collisions are more likely to have multiple interactions. The partons in the proton are assumed to be distributed according to a double-Gaussian as described in [19,17]. There are several parameters in this model and we have used the default setting for each.[1] Our strategy is to generate high-t photon exchange events (hard BFKL pomeron exchange has not been implemented in PYTHIA) with and without multiple interactions, and take the percentage change in the number of rapidity gap events, defined as in the DØ analysis, as the gap survival factor. We find that gap survival in this model is to first order independent of E_T^{jet} and $\Delta\eta$, i.e. it can be treated as a multiplicative factor. The gap survival factor $\mathcal{S}$ does vary strongly with centre of mass energy, which is not unexpected since the number density of partons in the colliding hadrons, and therefore the probability of having a secondary scatter, increases with energy. In summary, we find $\mathcal{S}(1800\text{ GeV}) = 22\%$, $\mathcal{S}(630\text{ GeV}) = 35\%$. Full details can be found in [20].

A key point to notice is the interplay between gap survival and underlying event : mul-

[1] Setting the switch `MSTP(82)=4` in PYTHIA , with everything else default, will give the model as we have used it.

tiple interactions also give rise to the so-called jet pedestal and underlying event effects. This means that the jets measured in hadron-hadron collisions cannot be compared directly to e.g. predictions from fixed order perturbation theory. In Figure 2 we show jet profiles obtained from PYTHIA with (mi4) and without (mi0) multiple interactions (and with $|\delta\phi| < 0.7$). The proton remnant is at $\delta\eta > 0$. It is clear that multiple interactions introduce a jet pedestal of more than 1 GeV of E_T per unit rapidity. For comparison, also shown is the jet pedestal from HERWIG . We note that HERWIG predicts a greater amount of energy outside the jet cone than PYTHIA without multiple interactions. Again, a full discussion of these differences can be found in [20].

In the DØ jet measurements the excess E_T from the underlying event is taken into account by correcting the jet E_T using minimum bias data. In particular, the correction is determined by looking at the E_T flow in regions away from the jets. The correction is made by subtracting approximately 1 GeV from the E_T of each reconstructed jet [21]. In particular, in the gap fraction measurement, this subtraction is performed for all jets, including those in gap events. But, requiring a large rapidity gap also selects events without multiple interactions, where the jet pedestal is absent, or at least much smaller; multiple interactions destroy gaps, and therefore a gap event *cannot have* a multiple interaction. Since jet cross sections fall faster than $1/E_T^4$, such a correction can decrease the measured jet rate by up to 30% for 18 GeV jets. Our contention therefore is that the jets in gap events should not be corrected for underlying event, and therefore the gap fraction should rise less steeply with E_T than in figure 1.

4. Gap fractions

Figures 3 and 4 show our results for the gap fractions as functions of $\Delta\eta$ and E_{T2} respectively. The stars are the HERWIG BFKL simulation with fixed $\alpha_s = 0.17$, with 1 GeV subtracted from each jet in order to simulate the DØ underlying event correction and the open circles are the DØ data. The gap fractions are constructed using a standard PYTHIA QCD simulation without colour singlet exchange, and without multiple interactions. We have used both CTEQ2M and CTEQ3M parton distribution functions [24,25], and have found the differences to be small. Our philosophy is that the DØ data have been corrected for the effects of multiple interactions in non-singlet exchange events, and we should therefore generate none, whereas we must undo the erroneous correction to the colour singlet sample. The combination

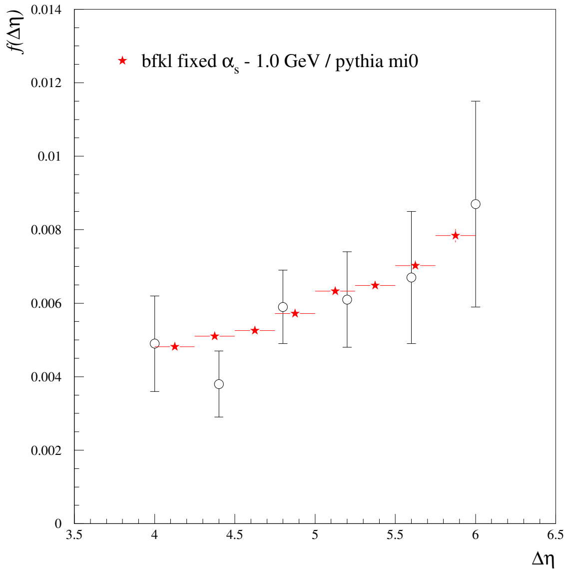

Figure 3. Gap fraction as a function of $\Delta\eta$ compared to the DØ data

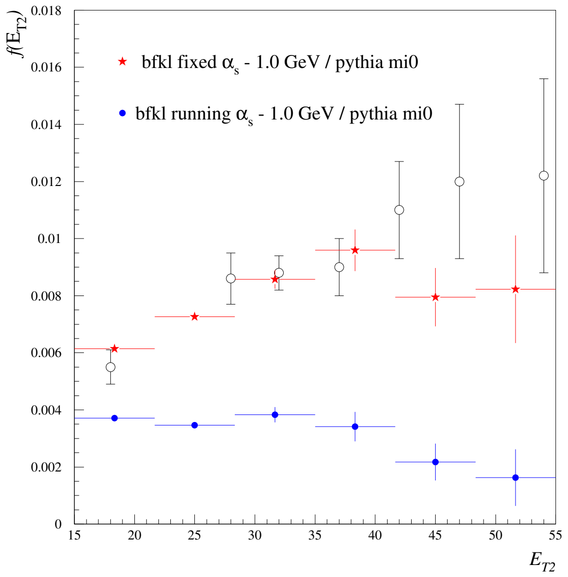

Figure 4. Gap fraction as a function of E_{T2} compared to the DØ data

of fixing α_s and correcting the gap events erroneously for multiple interactions produces the rise of the gap fraction at low jet E_T. The solid circles show the gap fraction using a running α_s in the BFKL sample. Even with the underlying event

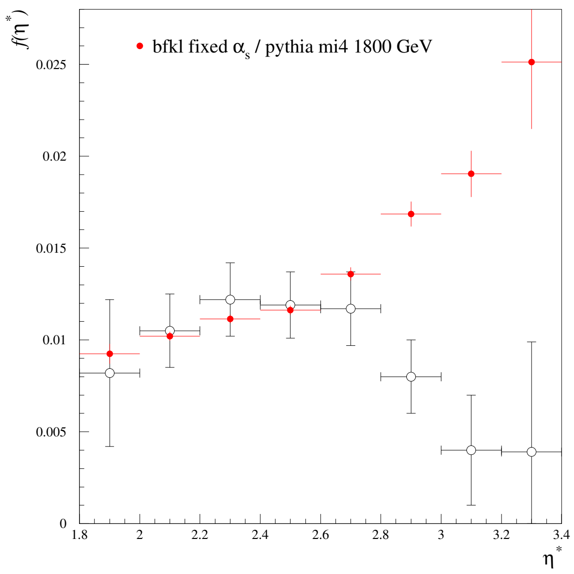

Figure 5. Gap fraction compared to the CDF data

correction, this sample is unable to fit the data. The overall normalisation of the simulated gap fractions is multiplied by a factor of 0.6. That this is a reasonable thing to do can be appreciated once it is realised that our results have not been fitted to the data and that the overall normalisation is acutely sensitive to the magnitude of α_s. Furthermore, the overall normalisation of the BFKL cross-section is uncertain since, within the leading logarithmic approximation, one does not know a priori the scale at which to evaluate the leading logarithms. Given these points, we conclude that the DØ data are in agreement with the leading order BFKL result. Figure 5 shows our result for the gap fraction as a function of $\Delta\eta \equiv 2\eta^*$ compared to the CDF data [4]. Note that CDF do not attempt to correct their jets to include the effect of an underlying event. We therefore generate the PYTHIA non-singlet sample with multiple interactions (labelled mi4), and do not perform the 1 GeV / jet subtraction from the HERWIG BFKL sample. In this plot, our theory points are obtained using a renormalisation factor of unity (compared to 0.6 in the DØ case). We then find reasonable agreement with the data except at the larger values of η^* where we are quite unable to explain a fall in the η^* distribution. Recall however that DØ do not see a fall at large $\Delta\eta$. Further clarification of the situation will require an increase in statistics.

We have also computed the ratio of the gap fractions at 630 GeV and 1800 GeV. We find that, even including gap survival effects, $R(630/1800) \sim 1$ at the parton level. When hadronisation effects are taken into account, however, we find that the ratio rises significantly to ~ 3, with a strong dependence on $\Delta\eta$. DØ find $R(630/1800) = 3.4 \pm 1.2$ [2], and CDF find $R(630/1800) = 2.4 \pm 0.9$. In the DØ case the effect may be attributed to the different parton x ranges of the 630 GeV and 1800 GeV measurements (although we note that the CDF result is calculated at fixed x). The restriction $x < 1$ forces the gap and non-gap cross-sections to fall to zero at some maximum $\Delta\eta$, $\Delta\eta_{\max}$. Now, the colour connection that exists between the jets in the non-gap sample drags the jets closer together in rapidity. This has a small effect away from $\Delta\eta_{\max}$ (since the $\Delta\eta$ spectrum is roughly flat) however as $\Delta\eta \to \Delta\eta_{\max}$ it leads to a more rapid vanishing of the non-gap cross-section than occurs in the gap cross-section. This effect, combined with the fact that $\Delta\eta_{\max}(630\text{ GeV}) < \Delta\eta_{\max}(1800\text{ GeV})$, leads to an enhancement of the measured 630 GeV gap fraction at large $\Delta\eta$ at the hadron level, and hence the larger value of $R(630/1800)$.

5. Conclusions and future possibilities

We have explicitly demonstrated that the Tevatron data on the gaps-between-jets process at both 630 GeV and 1800 GeV are in broad agreement with the predictions obtained using the leading order BFKL formalism. However, we are not able to explain the behaviour of the CDF gap fraction at large $\Delta\eta$. Agreement is obtained using the same fixed value of $\alpha_s = 0.17$ as was used to explain the recent HERA data on high-t double diffraction dissociation.

Care must be taken in the interpretation of our findings, however. The BFKL formalism itself suffers from being evaluated only to leading logarithmic accuracy. The uncertainties of the overall normalisation which follow will not be removed until an understanding of BFKL dynamics at non-zero t beyond the leading logarithmic approximation in achieved.

An understanding of the effects of underlying event and its impact on gap survival is crucial to the interpretation of the gaps between jets data, and indeed diffractive data as a whole.

As pointed out in [9,20], the gap fraction defined in terms of a region void of hadronic activity is not strictly infrared safe. A better observable would be to define a gap to be a region that does not contain any jets with transverse momenta above some perturbatively large scale. Work along these lines has also been performed in [26].

One major disadvantage of the gaps between jets process arises from the need to measure both jets since this limits the reach in rapidity. In [27], it was suggested to focus instead on the double dissociation sample (the gaps between jets events form a subsample of this generally much larger sample). By dropping the requirement to observe jets one not only gains in rapidity reach and statistics but also from the reduced systematics associated with this more inclusive observable.

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