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# Soft Colour Interactions and Diffractive Hard Scattering at the Tevatron

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ABSTRACT: We make a brief presentation of the soft colour interactions models, the Soft Colour Interaction and the Generalised Area Law, and summarise the results when they are applied to $p\bar{p}$ scattering. The models give a good description of the Tevatron data on production of $W$, bottom and jets in diffractive events, as well as jets with two rapidity gaps, alternatively leading particles. We also give predictions for diffractive $J/\psi$ production and discuss diffractive Higgs production at the Tevatron and LHC.

Diffractive hard scattering provides through its hard scale (high $E_T$ jets, $W$ and heavy quark production) the perturbative parton level basis for investigating non-perturbative effects. Diffraction, characterised by rapidity gaps and being a soft effect important on a long space-time scale, cannot be completely described by perturbative QCD. Traditionally, the observation of rapidity gaps in hard scattering has been explained in terms of the pomeron model [1], which works well in describing the HERA data, but fails to reproduce the Tevatron diffractive data when parametrisations of the pomeron structure functions and pomeron flux from HERA are used. Another characteristic signature of diffractive scattering is the presence of a leading particle carrying most of the beam particle momentum ($x_F \gtrsim 0.9$), which is kinematically related to a rapidity gap. Within the pomeron picture, the leading particle spectrum is given entirely by the pomeron flux, which has been shown to be non-universal.

A different approach is represented by the soft colour interactions models, based on the variations in the topology of the confining colour force fields: the soft colour interaction (SCI) model [2] and the generalized area law (GAL) model [3]. The SCI model is based on the assumption that partons emerging from the hard interaction can exchange colour with the proton colour field in which they propagate. In GAL, the interaction between overlapping strings is the basis for colour exchange. Both models lead to rearrangements of string topology, in the former with the probability $P$ to exchange a soft gluon between pairs of partons, in the latter with the probability for two strings to interact given by $P = P_0[1 - exp(-b\ \Delta A)]$, based on the Lund string model.

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[*] Speaker.

| Observable | $\sqrt{s}$ | | Ratio [%] | | |
|---|---|---|---|---|---|
| | [GeV] | Experiment | Observed | SCI | GAL |
| $W$ - gap | 1800 | CDF | $1.15 \pm 0.55$ | 1.2 | 0.8 |
| $Z$ - gap | 1800 | — | —[a] | 1.0 | 0.5 |
| $b\bar{b}$ - gap | 1800 | CDF | $0.62 \pm 0.25$ | 0.7 | 1.4 |
| $J/\psi$ - gap | 1800 | CDF | $1.45 \pm 0.25$ | 1.4 | 1.7 |
| $jj$ - gap | 1800 | CDF | $0.75 \pm 0.10$ | 0.7 | 0.6 |
| $jj$ - gap | 1800 | DØ | $0.65 \pm 0.04$ | 0.7 | 0.6 |
| $jj$ - gap | 630 | DØ | $1.19 \pm 0.08$ | 0.9 | 1.2 |
| gap - $jj$ -gap [b] | 1800 | CDF | $0.26 \pm 0.06$ | 0.2 | 0.1 |
| $\bar{p}$ - $jj$ -gap [b] | 1800 | CDF | $0.80 \pm 0.26$ | 0.5 | 0.4 |

**Table 1:** Ratios diffractive/inclusive for hard scattering processes in $p\bar{p}$ collisions at the Tevatron, showing experimental results from CDF and DØ [4, 5, 6] compared to the SCI and GAL soft color exchange models. *Legend:* [a] No result available; [b] Ratio of two-gap events to one-gap events.

Both models have been implemented in Monte Carlo event generators, LEPTO for $ep$ and PYTHIA for $p\bar{p}$ collisions. Using the standard Lund hadronisation the models lead to different hadronic final states, giving rise to events with or without gaps, leading protons or neutrons, etc. Thus they provide a unified description of all final states. They give a good description of rapidity gap events observed at HERA [2, 7], and good results when applied to hard diffractive $p\bar{p}$ scattering at the Tevatron [8]. An overall summary of the relative rates of various diffractive hard processes is given in Table 1, which shows that this approach can account for several different gap phenomena. It is noteworthy that the SCI model also reproduces the observed rate of high-$p_\perp$ charmonium and bottomonium at the Tevatron [9], as well as charmonium production in fixed target hadronic interactions [10].

The detailed description of the two soft colour models was presented at lenght in [8]. The only parameter of the models, represented by the colour exchange probability $P$, has been kept as fitted from diffractive DIS, although it was shown that the diffractive ratios are not sensitive to the exact value. Furthermore, for the case of $p\bar{p}$ scattering, the models include treatment of the remnants of the colliding hadrons and description of the soft underlying event, as developed for standard Monte Carlo programs, like PYTHIA.

An illustration of the effects of soft colour interactions, as well as a motivation for such modelling of the poorly known nonperturbative processes, is presented in Fig. 1. The very strong effect of hadronisation causes the large rapidity gaps present at the parton level (dashed curve), to be exponentially suppressed (dashed-dotted curve) in the hadronic final state after standard hadronisation. Applying the SCI model leads to an increased probability for large rapidity gaps (full curve), which is still far below the parton level result, but represents exactly what is needed to describe the data. The appearance of a 'diffractive plateau', taken as a characteristic for diffraction, is visible only when the kinematical constraint of the $W$ mass is relaxed (dotted curve, $m_W = 8$ GeV).

An experimental signature for diffraction is given by rapidity gaps. Events exhibiting one rapidity gap and having a hard scale ($W$, $b\bar{b}$, high-$E_T$ dijets) have been observed at the Tevatron [4]. We find that soft colour models give a good description of the relative rates of such events [8], i.e. the ratio between the cross-section for a diffractive process and the total cross-section for the same hard process (see Table 1).

A different signature of diffraction is a leading proton. The observation of leading antiprotons at the Tevatron [11], in events with high-$E_T$ jets, offered a new testing ground for the models. The agreement with data is good [8], when comparing the total ratio of diffractive to nondiffractive events, kinematical distributions of the dijets, and the dependence of the ratio with the momentum fraction $x$ of the interacting parton in $\bar{p}$. We find, however, an increased sensitivity of the latter with the details in the modelling of the remnant.

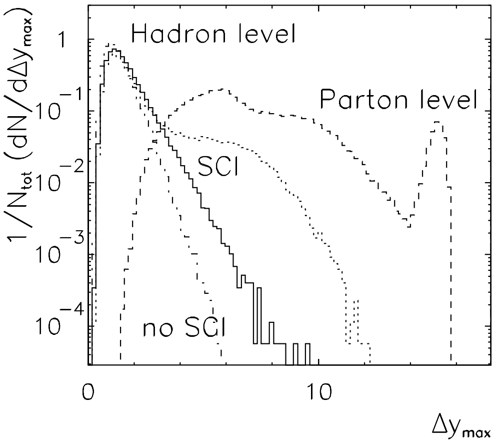

**Figure 1:** Distribution of the size $\Delta y_{max}$ of the largest rapidity gap in $W$ production in $p\bar{p}$ events at $\sqrt{s} = 1.8$ TeV in PYTHIA.

It is the events with *two* leading protons with associated gaps that will provide the ultimate test for the models. Such events, bearing the traditional name double Pomeron exchange (DPE) because of their description in the Regge framework, occur naturally in the soft colour interaction models. With one single mechanism for soft exchanges, the final colour string topology may give rise to two rapidity gaps, or two leading protons. Such Double leading Proton Events, with a dijet system in the central region, have been observed by CDF [6] and DØ.

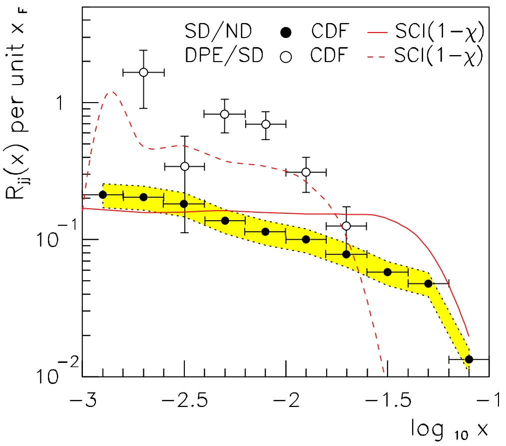

**Figure 2:** The ratio of DPE to single diffraction (per unit $x_F^p$) and the ratio of single diffraction to nondiffraction (per unit $x_F^{\bar{p}}$), as a function of the momentum fraction $x$ of the struck parton in $p$ and $\bar{p}$, respectively.

Apart from reproducing quite well the jet properties in inclusive nondiffractive (ND), single diffractive (SD) and DPE events, the models give also a reasonable description of the relative ratios between these types of events, and their cross-sections. For example, Fig. 2 gives a comparison of the CDF data with the SCI model using a certain parametrisation for the remnant treatment. Having two leading particles implies an increased sensitivity to the remnant treatment, providing possibilities to test and improve the details of the model.

The soft color interactions give rise to an even more striking effect of two different phenomena in the same event, namely both a rapidity gap and turning a colour octet $c\bar{c}$ pair into a singlet producing a $J/\psi$. It is a highly nontrivial result to explain both these effects with one model for non-pQCD dynamics. The predictions of our models are in agreement with the very recent observation by CDF [5] of such diffractive $J/\psi$ events (cf. Table 1).

Assuming a standard model Higgs exists, Higgs production in diffractive hard scattering has been argued to be useful for its discovery because of the Higgs signal standing out more clearly in the cleaner diffractive events. This holds especially for Higgs production in DPE events, where the underlying event has exceptionally low activity.

The existing predictions of the cross sections for these process vary by several orders of magnitude, so the central question in judging whether this is a useful Higgs channel, is whether the cross section is large enough. In contrast to all other available theoretical calculations of diffractive Higgs, our models have been tested against the available diffractive data from the Tevatron. This puts us in a better position to answer the question whether the diffractive Higgs channel is a feasible one at the Tevatron and at LHC [12].

| $m_H = 115$ | $\sqrt{s} = 1.96$ GeV<br>SCI/GAL | $\sqrt{s} = 14$ GeV<br>GAL/SCI |
|---|---|---|
| $\sigma_{tot}[fb]$ | 600 | 27000 |
| $R_H^{SD}[\%]$ | 0.2 | 0.6 - 0.7 |
| $\sigma_H^{SD}[fb]$ | 1.2 | 162 - 189 |
| $R_H^{DPE}[\%]$ | 0.01 - 0.02 | 0.1 |
| $\sigma_H^{DPE}[fb]$ | $1.2 - 2.4 \cdot 10^{-4}$ | 0.162 - 0.189 |

**Table 2:** Cross sections and ratios for diffractive Higgs production at the Tevatron and LHC for the soft color interaction models (using leading proton definition).

Table 2 shows our predictions for diffractive Higgs production, with a chosen mass of $m_H = 115$ GeV, in events associated with a leading proton (SD) or with two leading protons (DPE). With the luminosity to be achieved at the Tevatron in Run II, we conclude that only a few single diffractive Higgs events can be observed, and no DPE events. On the other hand, at the high CMS energy and luminosity available at the LHC, diffractive Higgs physics can be thoroughly studied, and DPE Higgs events will occur.

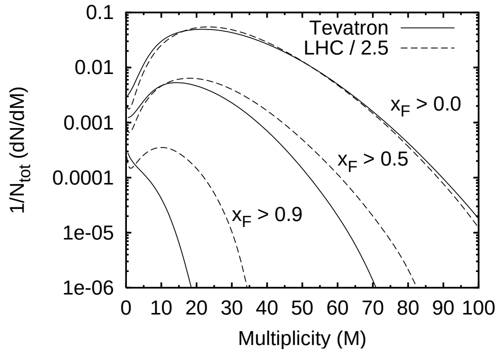

**Figure 3:** Multiplicity in the hemisphere of a leading proton with minimum $x_F$, for Higgs events from the SCI model in PYTHIA.

The quality of a diffractive event changes, however, at LHC energies. Besides the production of a hard subsystem and one or two leading protons, the energy is still enough for populating the expected rapidity gap regions with particles. As seen in Fig. 3, the multiplicity of particles in the rapidity region adjacent to the leading proton is considerably higher at the LHC, compared to the Tevatron. Thus, a 'clean' diffractive signal for Higgs may not be achieved without paying the price of a lower cross-section. Requiring one or two gaps induces a drop in the cross-section by a factor 10, respectively 100, compared to Table 2.

A new kind of rapidity gap events has been observed in $p\bar{p}$ collisions at the Tevatron [13], with a central rapidity gap spanned between two high-$E_T$ jets, corresponding to a large momentum transfer across the gap. The soft colour models cannot give a satisfactory description of this phenomenon, which needs to be explained in terms of a hard colour singlet exchange. Using a complete solution to the BFKL equation, which includes formally non-leading corrections (consistency constraint, running $\alpha_S$), the elastic parton-parton scattering amplitude via colour singlet resummed gluon-ladders can be obtained [14].

All soft effects, related to producing the hadronic final state, can now be taken into account, by implementing the BFKL solution into PYTHIA. As seen in Fig. 4, the BFKL solution gives a good description of the DØ data, with the Soft Colour Interaction model and Multiple Interactions providing a gap survival probability which varies event-by-event.

Our studies of the soft colour interaction models have demonstrated that they are able to reproduce a wide range of hard diffractive phenomena, at HERA and the Tevatron, from low scales ($J/\psi$) to high scales ($W$). Thus, the soft colour mechanism plays an important role in understanding the hadronic final state. Applying the models to diffractive Higgs production, we find cross-sections that are uninterestingly small at the Tevatron, but significant at the LHC.

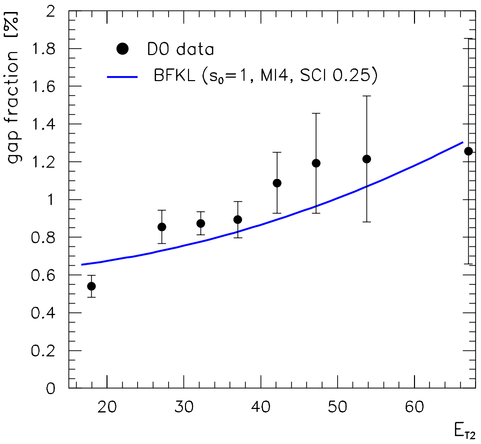

**Figure 4:** Fraction of jet events having a rapidity gap in $|\eta| < 1$ between the jets, versus the second highest jet-$E_T$.

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