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MULTIPLE INTERACTIONS AND BEAM REMNANTS*

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1. INTRODUCTION

Hadrons are composite systems of quarks and gluons. A direct consequence is the possibility to have hadron–hadron collisions in which several distinct pairs of partons collide with each other: multiple interactions, a.k.a. multiple scatterings. At first glance, the divergence of the perturbative t-channel one-gluon-exchange graphs in the $p_\perp \to 0$ limit implies an infinity of interactions per event. However, the perturbative framework does not take into account screening from the fact that a hadron is in an overall colour singlet state. Therefore an effective cutoff $p_{\perp\mathrm{min}}$ of the order of one to a few GeV is introduced, representing an inverse colour correlation distance inside the hadron. For realistic $p_{\perp\mathrm{min}}$ values most inelastic events in high-energy hadronic collisions should then contain several perturbatively calculable interactions, in addition to whatever nonperturbative phenomena may be present.

Although most of this activity is not hard enough to play a significant role in the description of high–$p_\perp$ jet physics, it can be responsible for a large fraction of the total multiplicity (and large *fluctuations* in it), for semi-hard (mini-)jets in the event, for the details of jet profiles and for the jet pedestal effect, leading to random as well as systematic shifts in the jet energy scale. Thus, a good understanding of multiple interactions would seem prerequisite to carrying out precision studies involving jets and/or the underlying event in hadronic collisions.

In an earlier study [1], it was argued that *all* the underlying event activity is triggered by the multiple interactions mechanism. However, while the origin of underlying events is thus assumed to be perturbative, many nonperturbative aspects still need to be considered and understood:
(i) What is the detailed mechanism and functional form of the dampening of the perturbative cross section at small $p_\perp$? (Certainly a smooth dampening is more realistic than a sharp $p_{\perp\mathrm{min}}$ cutoff.)
(ii) Which energy dependence would this mechanism have?
(iii) How is the internal structure of the proton reflected in an impact-parameter-dependent multiple interactions rate, as manifested e.g. in jet pedestal effects?
(iv) How can the set of colliding partons from a hadron be described in terms of correlated multiparton distribution functions of flavours and longitudinal momenta?
(v) How does a set of initial partons at some low perturbative cutoff scale, 'initiators', evolve into such a set of colliding partons? (Two colliding partons could well have a common initiator.) Is standard DGLAP evolution sufficient, or must BFKL/CCFM effects be taken into account?
(vi) How would the set of initiators correlate with the flavour content of, and the longitudinal momentum sharing inside, the left-behind beam remnant?
(vii) How are the initiator and remnant partons correlated by confinement effects ('primordial $k_\perp$')?
(viii) How are all produced partons, both the interacting and the beam-remnant ones, correlated in colour? Is the large number-of-colours limit relevant, wherein partons can be hooked up into strings (with quarks as endpoints and gluons as intermediate kinks) representing a linear confinement force [2]?
(ix) How is the original baryon number of an incoming proton reflected in the colour topology?

*submitted to the proceedings of the Workshop on Physics at TeV Colliders, Les Houches, France, 26 May – 6 June 2003 *(x)* To what extent would a framework with independently fragmenting string systems, as defined from the colour topology, be modified by the space–time overlap of several strings?

Needless to say, we should not expect to find a perfect solution to any of these issues, but only successively improved approximations. The framework in [1] is very primitive in a number of respects. Nevertheless, it has turned out to be quite successful. Thus the PYTHIA Tune A of R.D. Field [3] is capable of describing a host of jet and minimum-bias event data at the Tevatron. The model appears inadequate to fully describe correlations and fluctuations, however, and we would expect a poor performance for several topics not yet studied experimentally.

In particular, only very simple beam remnant structures could technically be dealt with in [1]. One recent development was the extension of the standard Lund string framework [2] to include a junction fragmentation description [4] that allows the hadronization of nontrivial colour topologies containing non-zero baryon number. In the context of multiple interactions, this improvement means that almost arbitrarily complicated baryon beam remnants may now be dealt with, hence many of the restrictions present in the old model are no longer necessary.

Here, we report on the development of a new model for the flavour-, colour-, and momentum-correlated partonic structure involved in a hadron–hadron collision, i.e. partly addressing several of the points above. We first present the main work on flavour and momentum space correlations, and thereafter separately the very thorny issue of colour correlations, before concluding. A more complete description of the model, also including references to experimental data and other theoretical ideas, and with comments on the all the issues, may be found in [5]. A toy model study of the first two points is found in [6]. The PYTHIA manual [7] contains some complementary information.

2. CORRELATED PARTON DENSITIES

Consider a hadron undergoing multiple interactions in a collision. Such an object should be described by multi-parton densities, giving the joint probability of simultaneously finding n partons with flavours $f_1, \ldots, f_n$, carrying momentum fractions $x_1, \ldots, x_n$ inside the hadron, when probed by interactions at scales $Q_1^2, \ldots, Q_n^2$. However, we are nowhere near having sufficient experimental information to pin down such distributions. Therefore, and wishing to make maximal use of the information that we *do* have, namely the standard one-parton-inclusive parton densities, we propose the following strategy.

As described in [1], the interactions may be generated in an ordered sequence of falling $p_\perp$. For the hardest interaction, all smaller $p_\perp$ scales may be effectively integrated out of the (unknown) fully correlated distributions, leaving an object described by the standard one-parton distributions, by definition. For the second and subsequent interactions, again all lower–$p_\perp$ scales can be integrated out, but the correlations with the first cannot, and so on. Thus, we introduce modified parton densities, that correlate the i'th interaction and its shower evolution to what happened in the $i-1$ previous ones.

The first and most trivial observation is that each interaction i removes a momentum fraction x_i from the hadron remnant. Already in [1] this momentum loss was taken into account by assuming a simple scaling ansatz for the parton distributions, $f(x) \to f(x/X)/X$, where $X = 1 - \sum_{i=1}^{n} x_i$ is the momentum remaining in the beam hadron after the n first interactions. Effectively, the PDF's are simply 'squeezed' into the range $x \in [0, X]$.

Next, for a given baryon, the valence distribution of flavour f after n interactions, $q_{f\mathrm{v}n}(x, Q^2)$, should integrate to the number $N_{f\mathrm{v}n}$ of valence quarks of flavour f remaining in the hadron remnant. This rule may be enforced by scaling the original distribution down, by the ratio of remaining to original valence quarks $N_{f\mathrm{v}n}/N_{f\mathrm{v}0}$, in addition to the x scaling mentioned above.

Also, when a sea quark is knocked out of a hadron, it must leave behind a corresponding antisea parton in the beam remnant. We call this a companion quark. In the perturbative approximation the sea quark $\mathrm{q_s}$ and its companion $\mathrm{q_c}$ come from a gluon branching $\mathrm{g} \to \mathrm{q_s} + \mathrm{q_c}$ (it is implicit that if $\mathrm{q_s}$ is a quark, $\mathrm{q_c}$ is its antiquark). Starting from this perturbative ansatz, and neglecting other interactions and any subsequent perturbative evolution of the $\mathrm{q_c}$, we obtain the q_c distribution from the probability that a sea quark $\mathrm{q_s}$, carrying a momentum fraction x_s, is produced by the branching of a gluon with momentum fraction y, so that the companion has a momentum fraction $x = y - x_\mathrm{s}$,

$$q_\mathrm{c}(x; x_\mathrm{s}) \propto \int_0^1 g(y)\, P_{\mathrm{g}\to\mathrm{q_s q_c}}(z)\, \delta(x_\mathrm{s} - zy)\, \mathrm{d}z = \frac{g(x_\mathrm{s}+x)}{x_\mathrm{s}+x}\, P_{\mathrm{g}\to\mathrm{q_s q_c}}\left(\frac{x_\mathrm{s}}{x_\mathrm{s}+x}\right) , \tag{1}$$

with $P_{\mathrm{g}\to\mathrm{q_s q_c}}$ the usual DGLAP gluon splitting kernel. A simple ansatz $g(x) \propto (1-x)^n/x$ is here used for the gluon. Normalizations are fixed so that a sea quark has exactly one companion. Qualitatively, $xq_\mathrm{c}(x; x_s)$ is peaked around $x \approx x_\mathrm{s}$, by virtue of the symmetric $P_{\mathrm{g}\to\mathrm{q_s q_c}}$ splitting kernel.

Without any further change, the reduction of the valence distributions and the introduction of companion distributions, in the manner described above, would result in a violation of the total momentum sum rule, that the x-weighted parton densities should integrate to X: by removing a valence quark from the parton distributions we also remove a total amount of momentum corresponding to $\langle x_{f\mathrm{v}} \rangle$, the average momentum fraction carried by a valence quark of flavour f,

$$\langle x_{f\mathrm{v}n} \rangle \equiv \frac{\int_0^X x q_{f\mathrm{v}n}(x, Q^2)\, \mathrm{d}x}{\int_0^X q_{f\mathrm{v}n}(x, Q^2)\, \mathrm{d}x} = X \, \langle x_{f\mathrm{v}0} \rangle , \tag{2}$$

and by adding a companion distribution we add an analogously defined momentum fraction.

To ensure that the momentum sum rule is still respected, we assume that the sea+gluon normalizations fluctuate up when a valence distribution is reduced and down when a companion distribution is added, by a multiplicative factor

$$a = \frac{1 - \sum_f N_{f\mathrm{v}n} \langle x_{f\mathrm{v}0} \rangle - \sum_{f,j} \langle x_{f\mathrm{c}_j 0} \rangle}{1 - \sum_f N_{f\mathrm{v}0} \langle x_{f\mathrm{v}0} \rangle} . \tag{3}$$

The requirement of a physical x range is of course still maintained by 'squeezing' all distributions into the interval $x \in [0, X]$. The full parton distributions after n interactions thus take the forms

$$q_{fn}\left(x, Q^2\right) = \frac{1}{X}\left[\frac{N_{f\mathrm{v}n}}{N_{f\mathrm{v}0}} q_{f\mathrm{v}0}\left(\frac{x}{X}, Q^2\right) + a\, q_{f\mathrm{s}0}\left(\frac{x}{X}, Q^2\right) + \sum_j q_{f\mathrm{c}_j}\left(\frac{x}{X}; x_{s_j}\right)\right] , \tag{4}$$

$$g_n(x) = \frac{a}{X} g_0\left(\frac{x}{X}, Q^2\right) , \tag{5}$$

where $q_{f\mathrm{v}0}$ ($q_{f\mathrm{s}0}$) denotes the original valence (sea) distribution of flavour f, and the index j on the companion distributions $q_{f\mathrm{c}_j}$ counts different companion quarks of the same flavour f.

After the perturbative interactions have taken each their fraction of longitudinal momentum, the remaining momentum is to be shared between the beam remnant partons. Here, valence quarks receive an x picked at random according to a small-Q^2 valence-like parton density, while sea quarks must be companions of one of the initiator quarks, and hence should have an x picked according to the $q_\mathrm{c}(x; x_\mathrm{s})$ distribution introduced above. In the rare case that no valence quarks remain and no sea quarks need be added for flavour conservation, the beam remnant is represented by a gluon, carrying all of the beam remnant longitudinal momentum.

Further aspects of the model include the possible formation of composite objects in the beam remnants (e.g. diquarks) and the addition of non-zero primordial $k_\perp$ values to the parton shower initiators. Especially the latter introduces some complications, to obtain consistent kinematics. Details on these aspects are presented in [5].

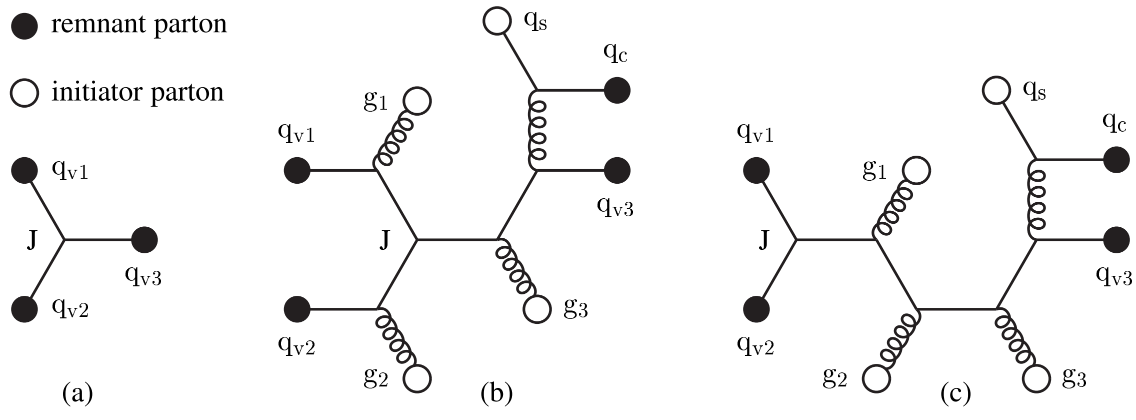

Fig. 1: (a) The initial state of a baryon, with the valence quarks colour-connected via a central string junction J. (b) Example of a topology with initiators connected at random. (c) Alternative with the junction in the remnant.

3. COLOUR CORRELATIONS

The initial state of a baryon may be represented by three valence quarks, connected antisymmetrically in colour via a central junction, which acts as a switchyard for the colour flow and carries the net baryon number, Fig. 1a.

The colour-space evolution of this state into the initiator and remnant partons actually found in a given event is not predicted by perturbation theory, but is crucial in determining how the system hadronizes; in the Lund string model [2], two colour-connected final state partons together define a string piece, which hadronizes by successive non-perturbative breakups along the string. Thus, the colour flow of an event determines the topology of the hadronizing strings, and consequently where and how many hadrons will be produced. The question can essentially be reduced to one of choosing a fictitious sequence of gluon emissions off the initial valence topology, since sea quarks together with their companion partners are associated with parent gluons, by construction.

The simplest solution is to assume that gluons are attached to the initial quark lines in a random order, see Fig. 1b. If so, the junction would rarely be colour-connected directly to two valence quarks in the beam remnant, and the initial-state baryon number would be able to migrate to large $p_\perp$ and small x_F values. While such a mechanism should be present, there are reasons to believe that a purely random attachment exaggerates the migration effects. Hence a free parameter is introduced to suppress gluon attachments onto colour lines that lie entirely within the remnant, so that topologies such as Fig. 1c become more likely.

This still does not determine the order in which gluons are attached to the colour line between a valence quark and the junction. We consider a few different possibilities: 1) random, 2) gluons are ordered according to the rapidity of the hard scattering subsystem they are associated with, and 3) gluons are ordered so as to give rise to the smallest possible total string lengths in the final state. The two latter possibilities correspond to a tendency of nature to minimize the total potential energy of the system, i.e. the string length. Empirically such a tendency among the strings formed by multiple interactions is supported e.g. by the observed rapid increase of $\langle p_\perp \rangle$ with n_{charged}. It appears, however, that a string minimization in the initial state is not enough, and that also the colours inside the initial-state cascades and hard interactions may be nontrivially correlated. These studies are still ongoing, and represent the major open issues in the new model.

4. CONCLUSION

A new model for the underlying event in hadron–hadron collisions [5] has been introduced. This model extends the multiple interactions mechanism proposed in [1] with the possibility of non-trivial flavour and momentum correlations, with initial- and final-state showers for all interactions, and with several options for colour correlations between initiator and remnant partons. Many of these improvements rely on the development of junction fragmentation in [4].

This is not the end of the line. Rather we see that many issues remain to understand better, such as colour correlations between partons in interactions and beam remnants, whereas others have not yet been studied seriously, such as the extent to which two interacting partons stem from the same initiator. Theoretical advances alone cannot solve all problems; guidance will have to come from experimental information. The increased interest in such studies bodes well for the future.

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