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Progress on Multiple Interactions

Modelling the underlying event in hadron–hadron collisions

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Abstract. We report on the development of a new model for the underlying event in hadron–hadron collisions. The model includes parton showers for all interactions, as well as non-trivial flavour, momentum, and colour correlations between interaction initiators and beam remnant partons.

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1 Introduction

A simple consequence of the composite nature of hadrons is the possibility to have hadron–hadron collisions in which several distinct pairs of partons collide with each other (multiple interactions). In fact, simple perturbative calculations can be used to show [1] that most inelastic events in high–energy hadronic collisions should 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 could be explained by the multiple interactions mechanism alone. However, while the origin of underlying events is thus assumed to be perturbative, many nonperturbative aspects still force their entrance on the stage. This in particular relates to the structure of beam remnants and to the correlations in flavour, colour, and momentum between the partons involved. In [1], only very simple beam remnant structures could technically be dealt with, hence substantial simplifications had to be imposed.

In recent years, the physics of the underlying event has come to attract more attention. Simple parameterizations can be tuned to describe the average underlying activity, but are inadequate to fully describe correlations and fluctuations. The increased interest and the new data now prompts us to develop a more realistic framework for multiple interactions than the one in ref. [1], while making use of many of the same underlying ideas.

One new aspect was the augmentation in [2] of the standard Lund string fragmentation framework [3] to include the hadronization of 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 present a model for how flavours, colours, and momenta are correlated between all the partons involved in a hadron–hadron collision, both those that undergo interactions and those constituting the beam remnants. However, all aspects of the model cannot be treated within the limits of this format, hence some aspects have been left out; we concentrate exclusively on baryon beams and neither the dependence on impact parameter nor the assignment of 'primordial $k_\perp$' to parton shower initiators is addressed here. More complete descriptions may be found in [4,5].

This article is organized as follows. In Section 2 the main work on flavour and momentum space correlations is presented and in 3 the very thorny issue of colour correlations. Finally, Section 4 provides a brief summary.

2 Towards a Realistic Model

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 follow the counting rule:

$$\int_0^X q_{f\mathrm{v}n}(x, Q^2)\ \mathrm{d}x = N_{f\mathrm{v}n}, \quad (1)$$

where $N_{f\mathrm{v}n}$ is the number 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 q_c distribution, 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 $x = y - x_\mathrm{s}$,

$$\begin{aligned} q_\mathrm{c}(x; x_\mathrm{s}) &= C \int_0^1 g(y)\, P_{\mathrm{g}\to\mathrm{q_s q_c}}(z)\, \delta(x_\mathrm{s} - zy)\ \mathrm{d}z \\ &= C\ g(y)\, P_{\mathrm{g}\to\mathrm{q_s q_c}}\left(\frac{x_\mathrm{s}}{y}\right)\frac{1}{y} \\ &= C\ \frac{g(x_\mathrm{s}+x)}{x_\mathrm{s}+x}\, P_{\mathrm{g}\to\mathrm{q_s q_c}}\left(\frac{x_\mathrm{s}}{x_\mathrm{s}+x}\right), \end{aligned} \quad (2)$$

with $P_{\mathrm{g}\to\mathrm{q_s q_c}}$ the usual DGLAP gluon splitting kernel and C a normalization constant which can be obtained by imposing the counting rule:

$$\int_0^{1-x_\mathrm{s}} q_\mathrm{c}(x; x_\mathrm{s})\ \mathrm{d}x = 1. \quad (3)$$

The exact form of C depends on the shape assumed for the gluon disitribution. Qualitatively, however, any falling gluon distribution $\propto 1/x$ convoluted with the almost flat $\mathrm{g} \to \mathrm{q\overline{q}}$ splitting kernel yields companion distributions which tend to a constant $q_\mathrm{c}(x; x_s) \sim C/2x_\mathrm{s}^2$ below x_s and which exhibit power-like fall-offs $q_\mathrm{c}(x; x_s) \propto 1/x^2$ above it, with some modulation of the latter depending on the large-x behaviour assumed for $g(x)$. Also note that $xq_\mathrm{c}(x; x_s)$ should be 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,

$$\int_0^X x\left(\sum_f q_{fn}(x, Q^2) + g_n(x, Q^2)\right)\mathrm{d}x = X, \quad (4)$$

since 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:

$$\langle x_{f\mathrm{v}n}\rangle \equiv \frac{\int_0^X x q_{f\mathrm{v}n}(x, Q^2)\ \mathrm{d}x}{\int_0^X q_{f\mathrm{v}n}(x, Q^2)\ \mathrm{d}x} = X\,\langle x_{f\mathrm{v}0}\rangle\ , \quad (5)$$

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

To ensure that eq. (4) 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. In addition, 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:

$$\begin{aligned} q_{fn}(x) = \frac{1}{X}\Bigg[&\frac{N_{f\mathrm{v}n}}{N_{f\mathrm{v}0}} q_{f\mathrm{v}0}\left(\frac{x}{X}\right) + a\, q_{f\mathrm{s}0}\left(\frac{x}{X}\right) + \\ &+ \sum_j q_{f\mathrm{c}_j}\left(\frac{x}{X}; x_{s_j}\right)\Bigg], \end{aligned} \quad (6)$$

$$g_n(x) = \frac{a}{X} g_0\left(\frac{x}{X}\right), \quad (7)$$

where we have suppressed the dependence on Q^2 for brevity, $q_{f\mathrm{v}0}$ ($q_{f\mathrm{s}0}$) 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. As already mentioned, the normalization factor a multiplying the gluon and sea distributions can be determined from overall momentum conservation in the incoming hadron:

$$a = \frac{1 - \sum_f N_{f\mathrm{v}n}\langle x_{f\mathrm{v}0}\rangle - \sum_{f,j}\langle x_{f\mathrm{c}_j 0}\rangle}{1 - \sum_f N_{f\mathrm{v}0}\langle x_{f\mathrm{v}0}\rangle}. \quad (8)$$

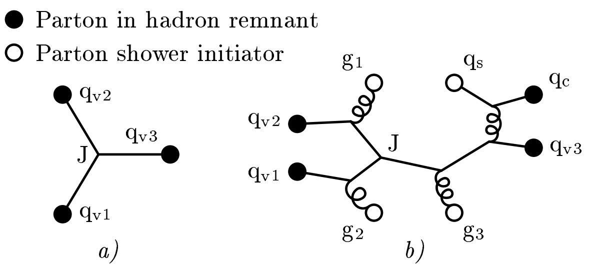

Fig. 1. *a)* The initial state of a baryon, consisting of 3 valence quarks conneted antisymmetrically in colour via a central 'string junction', J. *b)* Example of how a given set of parton shower intitators could have been radiated off the initial configuration, in the case of the 'purely random' correlations discussed in the text.

After the perturbative interactions have taken each their share of longitudinal momentum, the question arises how the remaining momentum is 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 $q_c(x; x_s)$ 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 will be presented in [5].

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. This situation is illustrated in Fig. 1a.

The precise colour-space evolution of this state into the initiator and beam 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 [3], 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 consequentially where and how many hadrons will be produced.

For the perturbative parts of the event, a unique colour flow may be consistently assigned [6], but for the connections among initiator and beam remnant partons, additional assumptions are necessary. 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 definition.

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. It should be clear that the migration of the baryon number depends sensitively upon which partons in the final state the junction ends up being connected to (see [2] for details on junction fragmentation). Thus, if the connections are *purely* random, the baryon number of the initial state should quite often be disconnected from the beam remnant altogether and be able to migrate to both large $p_\perp$ and small x_F values. Empirically, this may not be desireable, hence a free suppression parameter is introduced to suppress gluon attachments onto colour lines that lie entirely within the remnant.

Finally, we imagine a few different possibilities for the ordering of the emissions off a given colour line: 1) random, 2) gluons are ordered according to the rapidity of the hard scattering subsystem they are associated with (where beam remnant partons are assigned a fixed large rapidity in the direction of their parent hadrons), 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 represent different attempts to minimize the total potential energy of the system (the string length), since the former seems to result in a too large hadron multiplicity per interaction. A variable which we have found to be sensitive to the choice of colour topology is the average $p_\perp$ vs. n_{charged}, but our studies are not concluded yet. Thus, we do not pretend to have the final solution to these questions. Rather, the colour correlations, both in the initial and in the final state, still represents the major open issue in our studies.

4 Conclusion

The development of a new model for the underlying event in hadron–hadron collisions has been reported. This model extends the multiple interactions mechanism proposed in [1] with the possibility of non-trivial flavour and momentum correlations, parton showers for all initiator and final state partons, and several options for colour correlations between initiator and beam remnant partons. Many of these improvements rely on the development of junction fragmentation in [2].

The issue of colour correlations is still actively under study.

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