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A modified cluster-hadronization model ⋆

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A new phenomenological cluster-hadronization model is presented. Its specific features are the incorporation of soft colour reconnection, a more general treatment of diquarks including their spin and giving rise to clusters with baryonic quantum numbers, and a dynamic separation of the regimes of clusters and hadrons according to their masses and flavours. The distinction between the two regions automatically leads to different cluster decay and transformation modes. Additionally, these aspects require an extension of individual cluster-decay channels that were available in previous versions of such models.

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1 Introductory note

Multi-hadron and jet production in high-energy particle reactions is a basic property of the strong interaction [**?**,**?**]. A successful description relies on a factorization, which permits the separation of the perturbative evolution from the non-perturbative development of an event. The perturbative regime

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can be characterized through calculations of hard matrix elements and subsequent multiple parton emissions – the physically appealing parton-shower picture[1] . However the entire hadron-production mechanism cannot be precisely predicted because of the lack of the understanding of non-perturbative QCD effects, i.e. hadronization. For the transition of a coloured partonic system into colourless primary hadrons, this implies a need for phenomenological models. Lastly, after the primary-hadron genesis, decays of unstable hadrons are accomplished. Employing the separation ansatz, Monte Carlo event generators such as `JETSET/PYTHIA` [?] or `HERWIG` [?] proved to be a successful tool for the description of multiparticle generation in high-energy physics.

Concerning the transition process, such Monte Carlo schemes are either based on the Feynman–Field or independent fragmentation [?], on the Lund string [?] and UCLA [?] model (`JETSET/PYTHIA`), or on the cluster-hadronization model (`HERWIG`). The latter concept[2] , initially proposed by Wolfram and Field [?,?], and further advanced, among others [?], by Webber and Marchesini [?,?], explicitly rests upon the preconfinement property of QCD [?] and the LPHD hypothesis [?]. Such cluster models are usually formulated in terms of two phases: cluster formation accomplished through the non-perturbative splitting of gluons left by the parton shower into quark–antiquark pairs, and cluster decays leading to the additional creation of light-flavour pairs.

To understand the physics at present and future colliders, e.g. the Tevatron at Fermilab and the LHC at CERN, one fundamental cornerstone is the implementation of new Monte Carlo event generators, e.g. `PYTHIA7` [?,?,?], and `HERWIG++` [?,?,?]. The development of the `C++` Monte Carlo event generator `SHERPA` (Simulation of High Energy Reactions of PArticles) [?,?] is a step in the same direction. The modified phenomenological cluster-hadronization model presented in this paper contributes as a further module to the construction of the `SHERPA` package. The basic features of the new model are:

Soft colour reconnection is accounted for in the formation and decay of clusters. The flavour-dependent separation of the cluster regime from the region of hadron resonances yields the selection of specific cluster-transition modes. The two regimes are distinguished by comparing the mass of the cluster with the masses of the accessible hadrons matching the cluster's flavour structure. So far, the cluster scheme presented here is implemented only for electron–positron annihilation, and, for simplicity, only the light-quark sector is considered. An extension to heavy quarks, however, is straightforward.

The paper describing our cluster-hadronization model is organized as follows: first, different aspects of cluster formation are discussed in Sec. 2. Subsequently, in Sec. ??, the parametrization of light-flavour pair creation is presented. The model's description is concluded by exhibiting cluster transformation and fragmentation processes, which lead to the emergence of primary

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[1] Perturbative QCD cascades can be formulated in two complementary ways, either in terms of quarks and gluons or in terms of colour dipoles [?,?].

[2] Recent developments may be found, e.g. in [?].

hadrons, see Sec. **??**. The first results obtained with the new hadronization scheme are shown in Sec. **??** for the process $e^+e^- \to \gamma^\star/Z^0 \to d\bar{d}, u\bar{u}, s\bar{s} \to$ hadron jets.

2 Cluster formation

The parton shower describes multiple parton emission in a probabilistic fashion [**?**]. By factorizing the full radiation pattern into individual emissions it employs the large-N_C limit of QCD. This organizes a binary tree, i.e. a planar structure, of the partons. It also ensures that, once the colour structure of the initial partons from the hard matrix element is fixed, the colour structure of the partons at the end of the parton shower is unambiguously determined.
In our model, the non-perturbative transition of these partons into primary hadronic matter, clusters, is accomplished by the following steps:

(i) To guarantee the independence of the hadronization model from the quark masses eventually used in the parton shower and to account for a gluon mass needed by the model, all partons are brought to their constituent masses [**?**], $\mathcal{O}(0.3\ \mathrm{GeV})$, $\mathcal{O}(0.3\ \mathrm{GeV})$ and $\mathcal{O}(0.45\ \mathrm{GeV})$ for u, d and s flavours, and $\mathcal{O}(1\ \mathrm{GeV})$ for the gluon, respectively. For this transition a numerical method, involving several particles and consisting of a series of boosts and scaling transformations, is employed. However, these manipulations are applied only to parton-shower subsets that are in a colour-singlet state.

(ii) Since in cluster-hadronization models the clusters consist of two constituents in a colour-neutral state made up of a triplet–antitriplet, the gluons from the parton shower must split (at least) into quark–antiquark pairs [**?**]. So, a transition – in principle non-perturbative – transition $g \to q\bar{q}, \overline{D}D$ into a light quark–antiquark pair $q\bar{q}$ or a light antidiquark–diquark pair $\overline{D}D$ (see Sec. **??**) is enforced for each gluon. The respective flavour composition of the gluon's decay products is obtained with the same mechanism as used for cluster decays; see Sec. **??**. Quarks or diquarks that cannot be produced owing to too high masses are discarded. The kinematical distribution obeys axial symmetry; the energy fraction z of the quark (antidiquark) w.r.t. the gluon is given by a density proportional to $z^2 + (1-z)^2$, i.e. the gluon splitting function[3]. The limits on z are fixed only after the flavour of the decay products has been selected.

(iii) In contrast to the Webber model of cluster fragmentation [**?**], our model may also incorporate soft colour reconnection[4] effects by eventually re-

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[3] Obviously, for antidiquark–diquark pairs, this is a simplistic assumption, since it neglects, at least, the different spin structure of diquark production.

[4] Other soft colour reconnection models are presented, e.g. in [**?**,**?**].

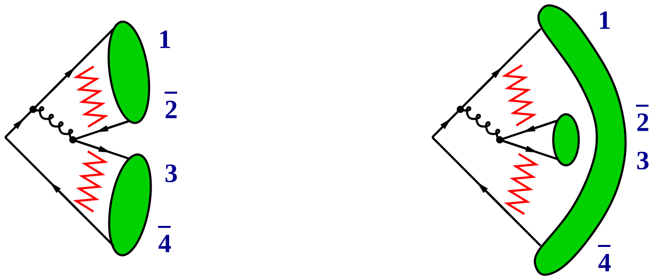

Fig. 1. Both options of cluster formation for a minimal $qg\bar{q} \to q\bar{q}'q'\bar{q}$ cascade. The zig-zag lines connecting the quark lines symbolize the soft exchange of colour quantum numbers, which is responsible for the colour reconnection.

arranging the colours of the partons forming the clusters. Starting with a simple cascade, Fig. 1 schematically shows the two options to arrange two colour neutral clusters out of four quarks or diquarks. The first – direct – case corresponds to the usual cluster formation and reflects the leading term in the $1/N_{\mathrm{C}}$ expansion. The second – crossed – configuration keeps track of subleading terms. Motivated by the well-known colour suppression of non-planar diagrams w.r.t. planar ones, the relative suppression factor due to colours is taken to be $1/N_{\mathrm{C}}^2$. Additionally, a kinematical weight is applied for each of the two possible cluster pairings. For the pairing ij, kl this weight reads