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Collectivity without plasma in hadronic collisions

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ABSTRACT

We present a microscopic model for collective effects in high multiplicity proton–proton collisions, where multiple partonic subcollisions give rise to a dense system of strings. From lattice calculations we know that QCD strings are transversely extended, and we argue that this should result in a transverse pressure and expansion, similar to the flow in a deconfined plasma. The model is implemented in the Pythia8 Monte Carlo event generator, and we find that it can qualitatively reproduce the long range azimuthal correlations forming a near-side ridge in high multiplicity proton–proton events at LHC energies.

1. Introduction

The general features of proton–proton collisions, such as jets, multiplicity distributions, and (approximate) particle ratios, can be described by dynamical models based on string [1] or cluster [2] hadronisation, *e.g.* Pythia8 [3,4] and Herwig7 [5], in a very satisfactory way. In contrast, heavy ion collisions show collective features interpreted as flow in a deconfined, thermalised plasma [6,7]. Nucleus collisions also show higher rates for strangeness [8]. These features have been interpreted as indicating fundamentally different dynamics in the two systems.

There are, however, also many similarities between collisions in small and in large systems. Many features in nucleus collisions, such as multiplicity distributions and particle distributions in rapidity and $p_\perp$, could fairly well be described by early models based on non-interacting strings (*e.g.* DPM [9] and Fritiof [10]). On the other hand recent precise measurements at the LHC show flow-like effects also in pp and pA collisions [11–13]. They also show increasing strangeness and baryon rates in pp events with high multiplicity [14]. This has raised the question if a QGP is formed also in small collision systems. Conversely, one could instead ask if collective effects in nucleus collisions could possibly originate from non-thermal interactions between string-like colour fields. This would entail a picture where collective phenomena does not arise from the formation of a deconfined QGP state, but rather as an emergent behaviour of dense configurations of confined QCD flux tubes. The aim of this letter is to investigate this possibility. A possible third option would be if the two pictures coexist, with a dense thermalised central "core" and an outer "corona". Such a picture is implemented in the quite successful EPOS model [15,16].

It was early suggested that the many strings in an AA collision may interact coherently as "ropes" [17]. Rope formation or "percolation" have subsequently been studied by several authors, see *e.g.* refs. [18–28]. Generally these analyses have predicted higher rates for strangeness and baryons, and larger transverse momenta, due to the stronger field in the rope.

The high energy density in overlapping strings also ought to give a transverse pressure, resulting in a transverse expansion seen as a transverse flow. This should give not only enhanced transverse momenta, in particular for high mass particles, but would also give rise to angular correlations. Such correlations were early considered by Abramovsky et al. [29], and a Monte Carlo "toy model" studying this effect in PbPb collisions was presented in refs. [30, 31]. A high string density can also be reached in pp and pA collisions at high enough energies, and Kalaydzhyan and Shuryak [32, 33] have suggested that a modification of the chiral condensate can cause an implosion, possibly resulting in an equilibrated plasma phase.

Rope formation in pp collisions was studied in ref. [28], and in ref. [34] we presented a proof of principle for a flow-like transverse expansion, due to overlapping strings in high energy pp collisions. In this letter we want use the concept of overlapping strings to study this effect more thoroughly, and compare the results with experimental data. To that effect we have implemented the re-

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sulting model in the Pythia8 event generator, and find that this dynamical mechanism indeed is able to produce the pp "ridge", first observed by the CMS collaboration [35].

2. The Lund string

The confining force field between coloured partons is in the Lund string model [1] described by a "massless relativistic string", which represents an idealised picture of a flux tube with no transverse extension. Like a linear electric field, the string is invariant under longitudinal boosts, and has no momentum in the direction of the string (apart from the force on the endpoints). Gluons are treated as point-like transverse excitations on the string [36], and for a set of colour connected partons, moving apart from a common origin, the string is stretched from a quark via the colour-ordered gluons to an antiquark.

The most simple situation is a quark and an antiquark produced in an e^+e^- annihilation, and moving apart. A string is stretched from the common production point, and breaks into pieces, hadrons, by repeated production of $q\bar{q}$ pairs, as sketched in Fig. 1. The boost invariant string is reflected in a boost invariant distribution of the hadrons. The spacetime separations between the production points are space-like, and in each frame the hadrons with the smallest energies in this specific frame, are produced first in time.

The probability for a specific final state is given by [37]

$$d\mathcal{P} \propto \exp(-bA) \times d\Omega. \tag{1}$$

Here bA is (the imaginary part of) the action for the relativistic string, with A equal to the space–time area (in units of the string tension κ) covered by the string before its breakup into hadrons (see Fig. 1). For a single hadron species with mass m, the n particle phase space Ω (in 1+1 dimensions) is given by $d\Omega = \prod_{i=1}^{n}[N\,d^2p_i\,\delta(p_i^2 - m^2)]\,\delta^{(2)}(\sum p_i - P_{\text{tot}})$. The parameter N here specifies the relation between the phase space for $n+1$ and n particles.

For a straight string the area A is easily expressed in terms of the hadron momenta, and the result can be generated by successively peeling off the hadrons from the quark or antiquark ends. Here each hadron is given a fraction z of the remaining light-cone momentum, determined by the distribution (in case of a single hadron species with mass m)

$$f(z) = Nz^a \exp(-bm^2/z). \tag{2}$$

The three parameters N, a, and b are related by normalisation, leaving two parameters to be determined by experiments.

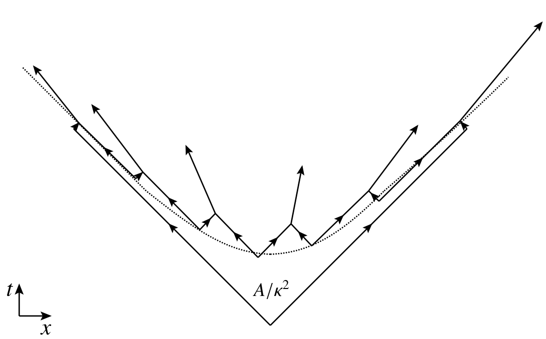

Fig. 1. Breakup of a string between a quark and an antiquark in a x–t diagram. New $q\bar{q}$ pairs are produced around a hyperbola, and combine to the outgoing hadrons. The original q and $\bar{q}$ move along light-like trajectories. The area enclosed by the quark lines is the coherence area A in eq. (1), in units of the string tension κ.

The breakup points for the string are located around a hyperbola in spacetime, with a typical proper time given by

$$\langle\tau^2\rangle = \frac{1+a}{b\kappa^2}, \tag{3}$$

where κ is the tension of the string. With values $a = 0.68$, $b = 0.98$ GeV^{-2} (the default values in Pythia8), and $\kappa = 0.9$–1 GeV/fm, we obtain the typical breaking time around 2 fm. Thus the string breaks typically when the original quark and antiquark are about 4 fm apart. The string then breaks in two pieces, which move apart keeping their size, with the new antiquark trailing after the initial quark increasing its energy due to the pull from the string, as illustrated in Fig. 1. Eventually the string breaks again, and in the successive breaks the string pieces become smaller and smaller.

3. Interactions between strings

The relativistic string is thought to represent the centre of a wider flux tube, similar to a vortex line in a superconductor. We note that just after the production of the initial $q\bar{q}$ pair, the colour field is necessarily compressed, not only longitudinally but also transversely. Also in a high energy pp collision the strings are stretched between charges emerging from a very limited region within two Lorentz contracted pancakes. As illustrated in Fig. 2, the flux tube expands both longitudinally and transversely with the speed of light. Two neighbouring flux tubes will then start to overlap and interact close to $z = 0$ (where z is the longitudinal coordinate) in the specific frame used in the analysis, as this is where the flux tube expands most rapidly. As seen in Fig. 1 this is also the region where those particles are produced, which are slow in this particular frame.

The repulsion gives the flux tubes a transverse velocity, a process which we will refer to as *shoving*. If the string density is high, strings in the centre feel a pressure from different sides. Therefore the outer strings start to move first, and only when they are further away the ones in the centre feel a net outward force. This is illustrated in Fig. 3, in which string shoving in three discrete time steps is sketched. In the end all potential energy from the overlapping flux tubes is transformed into kinetic energy. In a pp collision the density of strings is usually not too high, and the time until breakup ($\tau \sim 2$ fm) is large compared to both the width of the flux tubes and the radius of the proton (both < 1 fm). We therefore expect that the force field has (almost) reached its equilibrium

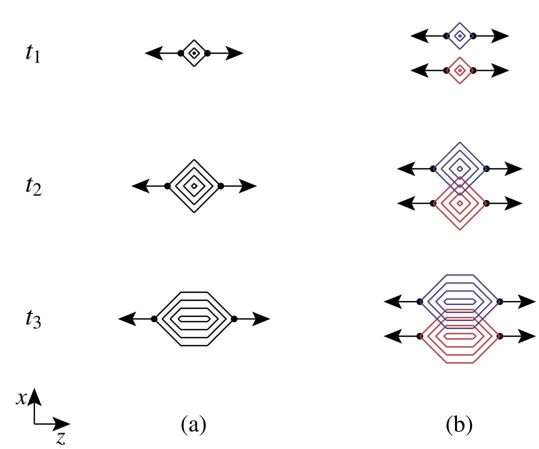

Fig. 2. (a) The forcefield between a quark and an antiquark separating from a common origin expands both longitudinally and transversely, until the transverse extension saturates. (b) The expansion is boost invariant. Therefore, in any frame two parallel flux tubes begin to overlap and interact in the centre in the specific frame chosen.