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Temporal evolution of tubular initial conditions and their influence on two-particle correlations in relativistic nuclear collisions

R.P.G. Andrade [a], F. Grassi [a,*], Y. Hama [a], W.-L. Qian [b]

[a] Instituto de Física, Universidade de São Paulo, Brazil
[b] Instituto de Ciências Exatas, Universidade Federal de Ouro Preto, Brazil

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ABSTRACT

Relativistic nuclear collisions data on two-particle correlations exhibit structures as function of relative azimuthal angle and rapidity. A unified description of these near-side and away-side structures is proposed for low to moderate transverse momentum. It is based on the combined effect of tubular initial conditions and hydrodynamical expansion. Contrary to expectations, the hydrodynamics solution shows that the high-energy density tubes (leftover from the initial particle interactions) give rise to particle emission in two directions and this is what leads to the various structures. This description is sensitive to some of the initial tube parameters and may provide a probe of the strong interaction. This explanation is compared with an alternative one where some triangularity in the initial conditions is assumed. A possible experimental test is suggested.

1. The need for a unified description

One of the most striking results in relativistic heavy-ion collisions at RHIC and the LHC, is the existence of structures in the two-particle correlations [1–8] plotted as function of the pseudorapidity difference $\Delta\eta$ and the angular spacing $\Delta\phi$. The so-called ridge has a narrow $\Delta\phi$ located around zero and a long $\Delta\eta$ extent. The other structure located opposite has a single or double hump in $\Delta\phi$. In order that two particles, emitted at some proper time $\tau_{f.out}$, appear as correlated over several rapidity units, the process that correlated them must have occurred [9,10] at a much smaller proper time due to causality. Therefore, the existence of long range pseudorapidity correlations must be related to early times in the nuclear collisions and thus has motivated many theoretical investigations.

Hydrodynamics has now been established as a good tool to describe many data from relativistic heavy-ion collisions so it should be able to provide a description for the above mentioned structures (for low to intermediate transverse momenta). In fact, as noted with RHIC data, a hydrodynamics based explanation is attractive because of the various similarities (see e.g. [11]) between bulk matter and ridge (transverse momentum spectra, baryon/meson ratio, etc.). In addition, it was shown (particularly at the LHC) that particle correlations can be understood in term of anisotropic flow Fourier coefficients [12–14]. This points towards the necessity to have a *unified* hydrodynamic description of near- and away-side structures.

In early models, it was suggested that the combined effect of longitudinal high-energy density tubes (leftover from initial particle collisions) and transverse expansion was responsible for the ridge [15,16,9,10,17]. The particle emission associated to the tube was expected to occur in a single direction, so this would cause a ridge but no away-side structure. In addition, the effect of hydrodynamics was usually assumed to be of a certain type (e.g. a blast wave in [9,10,17]) and in fact when hydrodynamic expansion was actually computed, it seemed to lead to a disappearance of the initial high-energy density tubes [18] and therefore of their particle emission.

In a previous work [19], we presented evidence that hydrodynamics might in fact reproduce all structures using the NeXSPheRIO code. This code starts with initial conditions from the event generator NeXus [20] and solves the hydrodynamic equations on an event-by-event basis with the method of Smoothed Particle Hydrodynamics. In [19], the NeXSPheRIO events were analyzed in a similar way to the experimental ones, in particular the ZYAM method was used to remove effects of elliptic flow. We later developed a different method to remove elliptic flow from our data and checked that all structures were indeed exhibited and other features well reproduced (dependence on the trigger- or associated-particle transverse momentum, centrality, in-plane/out-of-plane trigger, appearance of a peak on the ridge). However, when using NeXSPheRIO, it is not clear how the various structures in the two-particle correlations are generated. The aim of this Letter is to investigate this, studying in detail what happens

* Corresponding author.
E-mail address: grassi@if.usp.br (F. Grassi).

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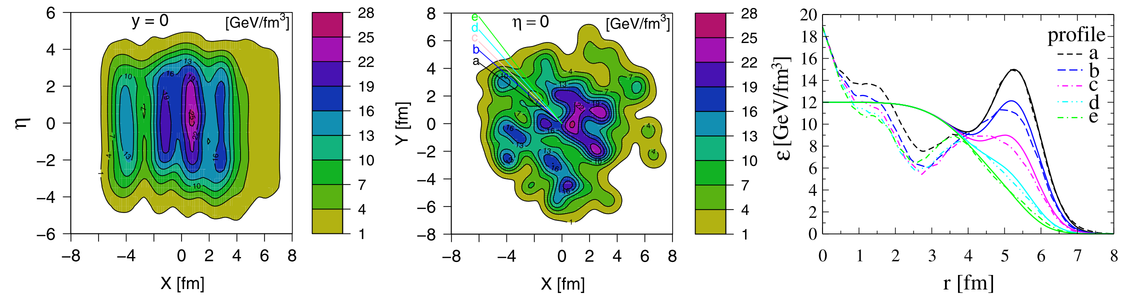

Fig. 1. Left and center: initial energy density for a NeXus central Au–Au collision at 200 GeV A in the $y=0$ and $\eta=0$ plane respectively. Right: comparison of the parametrization given by Eq. (1) (solid lines) with the original NeXus energy density (dashed lines), along the lines a–e (in the $\eta=0$ plane).

in the vicinity of an energetic tube (Section 2) and then extending the results to a more realistic complex case (Section 3). We will also compare our explanation with an alternative one that assumes some triangularity of the initial conditions (Section 4).

2. A simplified model

2.1. Origin of the near-side and away-side structures

We will consider central collisions only and use a simplified model. Fig. 1 (left and center) shows a typical example of initial conditions (initial energy density) obtained in NeXus with various tubular structures along the collision axis.

The origin of these structures is the following. To model soft physics in p–p collision, it is common to assume that strings (or color flux tubes) are formed, either via the excitation of the protons or due to color exchange between them. In A–A collisions, these strings may overlap leading to longitudinally extended regions of higher energy density such as those in Fig. 1. An alternative description of A–A collisions, based on gluon saturation, is that the two colliding nuclei can be viewed as Color Glass Condensates. Shortly after their collision, these produce strong color flux tubes called “Glasma”. Therefore the possibility that tubular structures exist in the initial conditions is general but their exact characteristics are not known.

In the simplified model, only one of the high-energy tubes from NeXus (chosen close to the border) is considered and the complex background is smoothed out. This leads to the following parametrization of the initial energy density

$$\epsilon = 12\exp\left(-0.0004r^5\right) + \frac{34}{0.845\pi}\exp\left(\frac{-|\vec{r}-\vec{r}_0|^2}{0.845}\right), \qquad (1)$$

where $r_0 = 5.4$ fm. A comparison of this parametrization with the original NeXus energy density is shown in Fig. 1 (right). Except for the inner region (which has little importance cf. Section 2.2), the agreement is reasonable. We use this parametrization in order to have a realistic tube description. However as already mentioned, the exact characteristics of the color tubes are not well known, therefore later we will consider various variations of the parameters.

In this simplified model or one-tube model, transverse expansion is computed numerically while longitudinal expansion is assumed boost-invariant, until freeze out at some constant temperature. The resulting single-particle angular distribution, shown in Fig. 2 (top), has two peaks located on both sides of the position of the tube (placed at $\phi=0$) with separation ~ 2 (this is not a parameter), more or less independently of the value of the transverse momentum. Particle emission is computed assuming sudden freeze out. Since this is an approximation to real particle emission, we have checked that varying the freeze out temperature

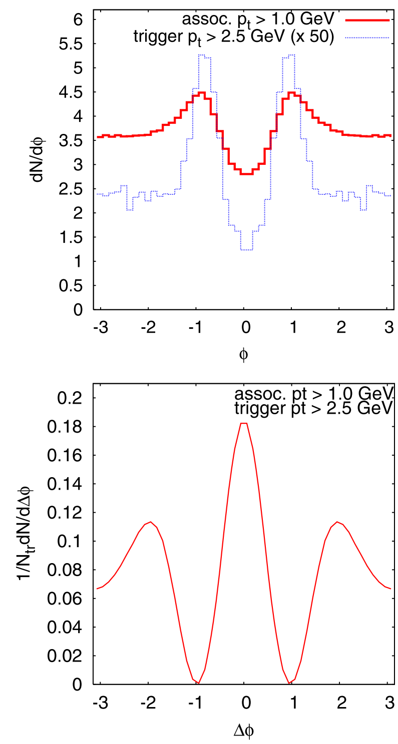

Fig. 2. Angular distributions of (direct) charged particles in some different p_T intervals (top) and resulting two-particle correlations (bottom) in the simplified model (for a freeze out temperature of 0.14 GeV).

(between 130 and 150 MeV) does not affect qualitatively our result.

This two-peak emission is in contrast with what happens when a blast wave is assumed, namely the fact that high-energy tubes emit in a single direction. However, its occurrence can be understood from Fig. 3. As time goes on, as a consequence of the tube expansion, a hole appears at the location of the high-energy tube (as in [18]). This hole is surrounded by matter that piles up in a roughly semi-circular cliff of high-energy density matter, guiding the flow of the background matter into two well-defined directions. The two extremities of the cliff emit more particles than the background, this gives rise to the two peaks in the single-particle angular distribution. The emission is not quite radial as shown by Fig. 3 (right), indicating that there was a deflection of the background flow due to the pressure exerted by the high-energy tube. As seen in Fig. 3, the fluid velocity is larger at the two extremities of the cliff and smaller nearby, this is why in Fig. 2 the angular distribution is narrower for larger p_t particles.

From Fig. 2 (top), we can guess how the two-particle angular correlation will be. The trigger particle is more likely to be in one