Importance of Granular Structure in the Initial Conditions for the Elliptic Flow

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We show the effects of the granular structure of the initial conditions of a hydrodynamic description of high-energy nucleus-nucleus collisions on some observables, especially on the elliptic-flow parameter v_2. Such a structure enhances production of isotropically distributed high-p_T particles, making v_2 smaller there. Also, it reduces v_2 in the forward and backward regions where the global matter density is smaller and, therefore, where such effects become more efficacious.

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Introduction.—It is by now widely accepted that hydrodynamics is a successful approach for describing the collective flow in high-energy nuclear collisions. The basic assumption in hydrodynamical models is the local thermal equilibrium. It is assumed that, after a complex process involving microscopic collisions of nuclear constituents, at a certain early instant a hot and dense matter is formed, which would be in local thermal equilibrium. Usually, this state is characterized by some initial conditions (IC), parametrized as smooth distributions of thermodynamic quantities and four-velocity. After this instant, the system would evolve hydrodynamically, following the well-known set of differential equations.

However, since our systems are not large, important event-by-event fluctuations are expected in real collisions. Concerning this question, fluctuation in the IC deserves a special consideration. In the past few years, we have studied several effects caused by such fluctuating IC on observables, by using a computational code especially developed for this purpose, which we call NEXSPHERIO [1–5]. In particular, in [1] we have studied the fluctuations of the so-called elliptic-flow parameter v_2, showing that they are quite large, which has been confirmed by recent data [6,7]. Our more recent computations gave similar results [8].

An important point with regard to such IC for high-energy nuclear collisions is that they are not only event-by-event fluctuating, but also are strongly inhomogeneous in space. Since the incident nuclei are not smooth objects, if the thermalization is verified at very early time as usually assumed in hydrodynamic approach, they could not be smooth but should have granular structure. In the present Letter, we focus our attention mainly to such a granular structure of fluctuating IC and try to show important effects on some observables, especially on the elliptic-flow parameter v_2.

In what follows, we will first give a brief discussion on what is expected if such hot blobs are produced. We shall then proceed describing our main tool, the NEXSPHERIO code. We then show the results of computations, first on transverse-momentum (p_T) spectra, and then on v_2 as function both of pseudorapidity η and of p_T. Finally, the main conclusions are drawn.

What is expected from the hot blobs?—What do we expect if the IC present granular structure as depicted in Fig. 1? Because of the high concentration of energy in *pointlike* regions, we imagine that initially each blob would suffer a violent explosion and, because of their small size, expand isotropically. If one of such blobs is deep inside the hot matter, this initial motion is quickly absorbed by the surrounding medium, so it would not result in any observable effect. However, if such a blob is at the surface of the matter, certainly the outgoing part of this initial acceleration would remain, producing high-p_T particles, which would be isotropically distributed in the momentum space.

Thus, first we expect that high-p_T part of the p_T spectra is enhanced when fluctuating IC are used in our computations, in comparison with the results with averaged (smooth) IC. In the second place, we expect that the anisotropic-flow coefficient v_2 suffers reduction as we go to the high-p_T region, due to the additional high-p_T iso-

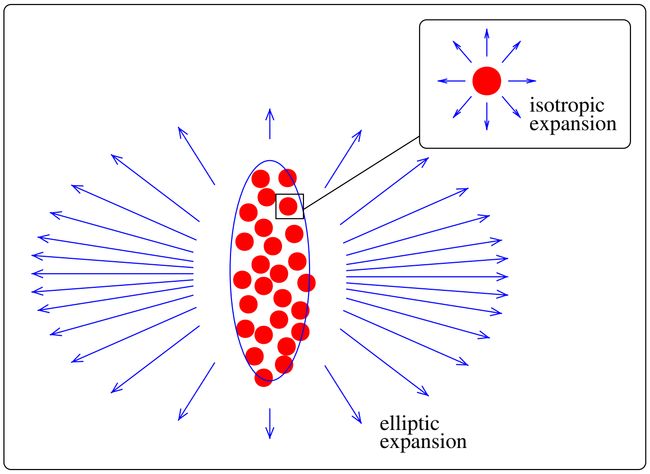


FIG. 1 (color online). Pictorial representation of the energy-density distribution in a fluctuating IC.

tropic component included now. As for the η dependence of v_2, we know that the average matter density decreases as $|\eta|$ increases as reflected in the η distribution of charged particles, so when such a blob is formed in the large-$|\eta|$ regions, its effects appear more clearly. Therefore, we expect considerable reduction of v_2 in those regions.

Although not discussed here, the granular structure we are considering certainly affects the so-called Hanbury Brown–Twiss radii. This question has been discussed in a previous publication [2].

NEXSPHERIO code.—Our fundamental tool for the present study is called NEXSPHERIO. It is a junction of two computational codes: NEXUS and SPHERIO. The NEXUS code [9] is used to compute the IC: $T^{\mu\nu}$ and j^{μ} on some initial hypersurface. It is a microscopic model based on the Regge-Gribov theory, and the main advantage for our purpose is that, once a pair of incident nuclei or hadrons and their incident energy are chosen, it can produce, in the event-by-event basis, detailed space distributions of the energy-momentum tensor, baryon number, strangeness, and charge densities, at a given initial time $\tau = \sqrt{t^2 - z^2} \sim 1$ fm. We remark that, when we use a microscopic model to create a set of IC for hydrodynamics, the generated energy-momentum tensor does not necessarily correspond to that of local equilibrium, so we need to transform it to that of the equilibrated matter, adopting some procedure as described in detail in Ref. [10].

We show in Fig. 2 an example of such a fluctuating event, produced by the NEXUS event generator, for a central Au + Au collision at 130A GeV, compared with an average over 30 events. As can be seen, the energy-density distribution for a single event (left), at the midrapidity plane, presents several blobs of high-density matter, whereas in the averaged IC (right) the distribution is smoothed out, even though the number of events is only 30. The latter would correspond to the usually adopted smooth and symmetrical IC in many hydrodynamic calculations. The bumpy event structure, as exhibited in Fig. 2, was also shown in calculations with HIJING [11] and other event generators. As already observed there and studied in [1–5,10], this bumpy structure gives important consequences in the observables. As for the velocity distribution, it gives essentially zero transverse velocity and longitudinal component close to the boost-invariant one.

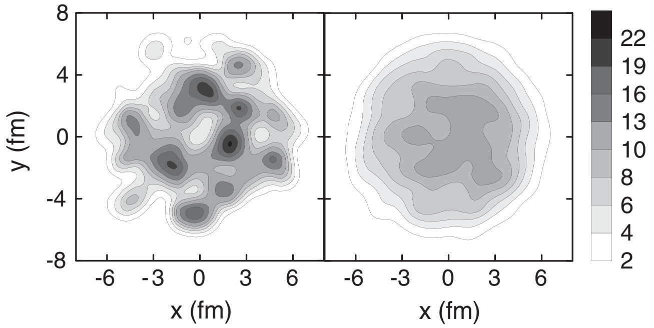


FIG. 2. Examples of initial conditions for central Au + Au collisions given by NEXUS at the midrapidity plane. The energy density is plotted in units of GeV/fm^3. Left: one random event. Right: average over 30 random events (corresponding to the smooth initial conditions in the usual hydro approach).

Solving the hydrodynamic equations for events so irregular as the one shown in Fig. 2 requires special care. The SPHERIO code is well suited to computing the hydrodynamic evolution of such systems. It is based on smoothed particle hydrodynamics, an algorithm originally developed in astrophysics [12] and adapted to relativistic heavy ion collisions [13]. It parametrizes the flow in terms of discrete Lagrangian coordinates attached to small volumes (called “particles”) with some conserved quantities. Its main advantage is that any complex geometry and violent dynamics such as shock phenomena can be treated without any numerical difficulties, when the size of particles is appropriately chosen [13].

Now, we have to specify some equation of state (EOS) describing the locally equilibrated matter. Here, in accordance with Ref. [4], we will adopt a phenomenological implementation of the EOS, giving a critical end point in the quark-gluon plasma–hadron gas transition line, as suggested by the lattice QCD [14].

We shall neglect in this paper any dissipative effects and also assume the usual sudden freeze-out (both chemical and kinetic) at a constant temperature. As for the conserved quantities, besides the energy, momentum, and entropy, we consider just the baryon number. Although very simplified, we believe that the main outcomes of the present study will remain valid in more detailed description, including refinements in EOS.

In computing several observables, we perform in the present work two sets of computations: (i) First, we average over random NEXUS events, obtaining smooth IC, which are used to compute the observables by using the SPHERIO code. This is similar to the usual hydro calculation. (ii) In the second set, NEXSPHERIO is run many times and an average over final results is performed. This mimics experimental conditions more closely. We remark that in the latter the granular structure of IC, mentioned above, is being explicitly included whereas in the former it is not.

Having depicted our tool, let us now explain how we fix the parameters of the model and compute the observables of our interest. Certainly any model to be considered as such should reproduce the most fundamental, global quantities involving the class of phenomena for which it is proposed. So, we begin by fixing the initial conditions so as to reproduce properly the (pseudo-)rapidity distributions of charged particles in each centrality window. This is done by applying an η-dependent factor ~ 1 to the initial energy-density distribution of all the events of each centrality class, produced by NEXUS (see Ref. [8]). Next, we would like to correctly reproduce the transverse-

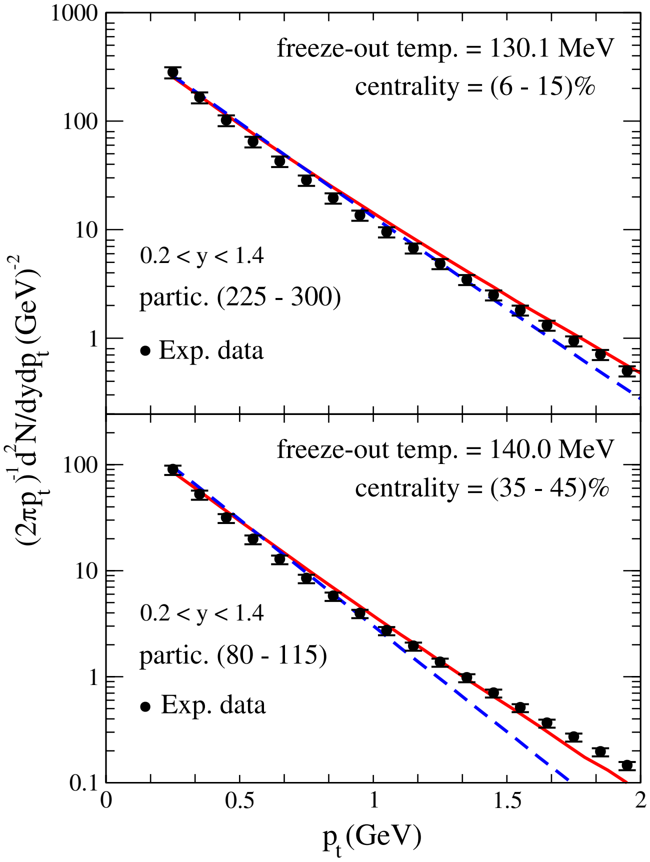
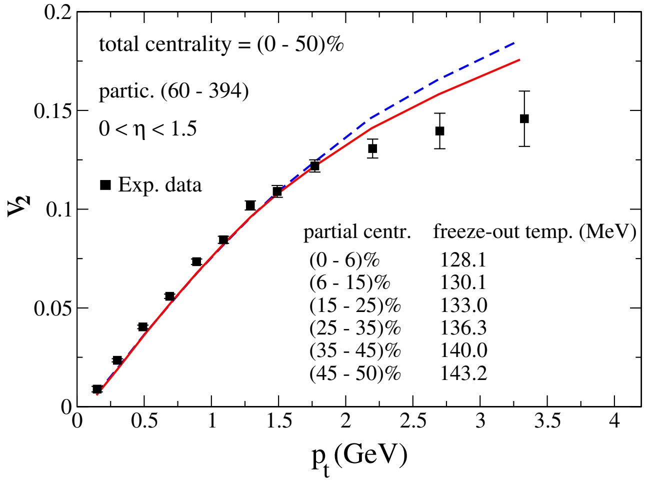


FIG. 3 (color online). Charged-particle p_T distributions (including those from resonance decays), in two different centrality windows, computed in two different ways as explained in the text. The solid lines indicate results for event-by-event fluctuating IC, the dashed lines the ones for the averaged IC. The data points [22] are also plotted for comparison.



partial centr.	freeze-out temp. (MeV)
(0 - 6)%	128.1
(6 - 15)%	130.1
(15 - 25)%	133.0
(25 - 35)%	136.3
(35 - 45)%	140.0
(45 - 50)%	143.2

FIG. 4 (color online). p_T dependence of $\langle v_2 \rangle$ in the centrality window and η interval as indicated, compared with data [19]. The solid line indicates the result for fluctuating IC, the dashed one that for the averaged IC. The curves are averages over PHOBOS centrality subintervals with freeze-out temperatures as indicated.

momentum spectra of charged particles, which can be achieved by appropriately parametrizing the centrality dependent freeze-out temperature as $T_{\rm fo} = 192.2\langle N\rangle^{-\alpha}$, where N is the participant-nucleon number. The power-law behavior of $T_{\rm fo}$ was suggested in a previous work [15], by considering a massless pion gas, for which $\alpha = 1/6$. The best fit with data now gave $\alpha = 0.07$.

Results.—

Charged-particle spectra.—We show in Fig. 3 our results for the charged-particle spectra in two different centrality windows as indicated, computed as explained on the previous page. It is clearly seen that, as one goes from the smooth averaged IC to bumpy fluctuating IC, the high-p_T component of the spectra increases as expected, making them more concave and closer to the data.

p_T dependence of $\langle v_2 \rangle$.—In Fig. 4, we show our results for the p_T dependence of $\langle v_2 \rangle$ in the centrality window and η interval as indicated. Here, since our purpose is to show clearly the effects of granular IC, we plot the results obtained with the same PHOBOS hit-based method for the both curves, but without any correction for event-plane fluctuations. While the result with smooth averaged IC shows a continuous increase of $\langle v_2 \rangle$ with p_T, deviating largely from the data points, as happens in the orthodox hydro computations, the introduction of spiky IC makes v_2 smaller at high p_T as expected, approaching the curve to the data points. The correction mentioned above shifts the curve upward, corresponding to the fluctuating IC, but without modifying its shape. The fact that the averaged smooth IC lead to rising $v_2(p_T)$ for large p_T and not flattening is usually interpreted as a breakdown of the hydrodynamic model. We suggest it could be in part related to the granular structure of the IC.

η dependence of $\langle v_2 \rangle$.—In Fig. 5, we show our results for the η dependence of $\langle v_2 \rangle$ in three different centrality windows as indicated. As in Ref. [5], we calculated $\langle v_2 \rangle$ with respect to the event plane as done experimentally. The event plane has been determined here by all the charged particles (the results with the PHOBOS hit-based method with correction are almost identical). For averaged smooth IC, in agreement with the usual hydro computations [16–18], $\langle v_2 \rangle$ exhibits shoulders in high-$|\eta|$ regions. When fluctuating spiky IC are used, these shoulders are considerably weakened as expected. The results, which combine this and the complementary effect of increase of $\langle v_2 \rangle$ with the event-plane fluctuations, are now closer to the data of Ref. [19].

Another important ingredient of a hydrodynamic model is the decoupling procedure. We are studying the effect of *continuous emission* [20]. Probably it makes the curve of v_2 at high-p_T even flatter and the η-distribution narrower [4]. This is clear, also in Refs. [17,18,21], where they use the usual smooth IC and, by describing the decoupling with a microscopic transport model, could improve v_2 in this

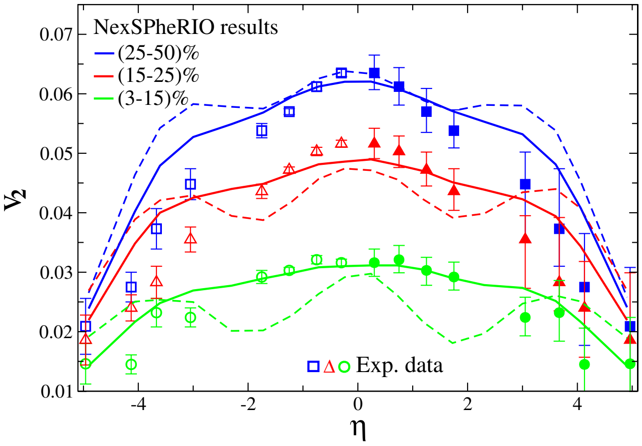


FIG. 5 (color online). η dependence of $\langle v_2 \rangle$ for three centrality windows. The solid lines indicate results for event-by-event fluctuating IC, the dashed lines the ones for the averaged IC. The data points [19] are also plotted for comparison. $T_{\rm fo}$ has been taken as indicated in Fig. 4.

direction. The cascade model in the hadronic stage produces similar effects as the continuous emission.

Conclusions.—While it is believed that a granular structure exists in the IC, hydro simulations are usually done with smooth IC, the expectation being that the granularity will not manifest itself. In this Letter, we argue that this may not be true.

The main conclusions of the present study are (i) Granular structure in the IC produces more high-p_T particles, distributed isotropically. (ii) Granular structure in the IC reduces the elliptic flow, because of the isotropic flow it generates. (iii) As a function of p_T, the mechanism becomes more effective as p_T increases, because those high-density blobs cause violent expansion, producing high-p_T particles. (iv) This effect is enhanced where the average matter density is small. So, it decreases v_2 in the large pseudorapidity regions. (v) NEXSPHERIO, with fluctuating and spiky IC, improves significantly the results of p_T spectra and p_T- and η-dependences of v_2 for different centrality windows, making them closer to data.

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