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FLUCTUATIONS AND INITIAL STATE GRANULARITY IN HEAVY ION COLLISIONS AND THEIR EFFECTS ON OBSERVABLES FROM HYDRODYNAMICS*

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A comparison is made between results obtained using smooth initial conditions and event-by-event initial conditions in the hydrodynamical description of relativistic nuclear collisions. Some new results on directed flow are also included.

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1. Objective

Hydrodynamics has been rather successful at describing data obtained in relativistic nuclear collisions at RHIC. Usually, smooth initial conditions are assumed (see *e.g.* Fig. 1 in [1] and Fig. 3 in [2]). On the other side, microscopic codes such as NeXus predict initial conditions event-by-event, which are quite irregular as shown in Fig. 1.

The question we address here is whether such structures (hot spots or more precisely hot tubes) can have a sizable effect on variables.

To solve the hydro equations with very irregular initial conditions, we use the SPheRIO code. This code is based on the method of Smoothed Particle Hydrodynamics, originally developed in astrophysics and adapted to relativistic heavy ion collisions in [3]. The version of NeXSPheRIO used here has

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initial conditions provided by NeXus [4] and normalized by an η-dependent factor to reproduce $dN_{\rm ch}/d\eta$ in each centrality window [5]. The equation of state has a critical point [6]. $T_{\rm f.out}$ is fixed (mostly) by $dN_{\rm ch}/p_{\rm t}dp_{\rm t}$ and depends on the centrality window (*i.e.* number of participants). Centrality windows are defined using participant number and not impact parameter [7]. An ideal fluid is assumed, a code with Smoothed Particle Hydrodynamics and dissipation is under development [8].

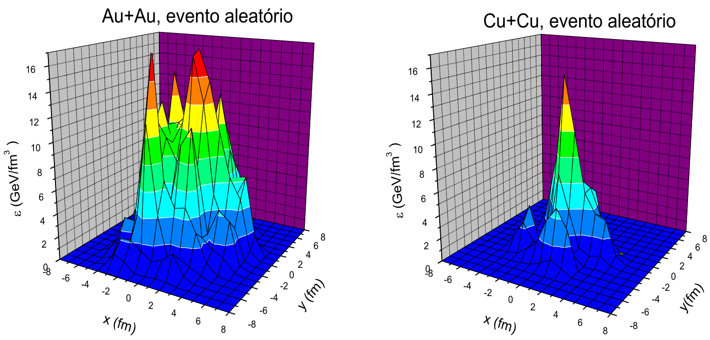

Fig. 1. $\eta = 0$ slice for initial energy density of a RHIC collision in the 6–15% centrality window.

2. Comparison between fluctuating and average IC

In the following, we present a summary of results obtained using smooth initial conditions and running once the SPheRIO hydro code (standard approach) or using a set of NeXuS initial conditions, running for each initial conditions the SPheRIO hydro code and computing averages over the set for various observables (event-by-event hydrodynamics).

2.1. $p_{\rm t}$ distribution

As can be seen in Fig. 2 (left), the high $p_{\rm t}$ part is lifted. This is expected since hot tubes must expand more violently, producing more high $p_{\rm t}$ particles [9, 10].

2.2. elliptic flow

$v_2(p_{\rm t})$ is flatter as seen in Fig. 2 (centre). This is also expected as the isotropic expansion of hot tubes produces more high $p_{\rm t}$ particles and lowers $v_2(p_{\rm t})$ [9,10]. In addition, $v_2(\eta)$ has no shoulder [11] as seen in Fig. 2 (right). The effects (isotropic expansion) of the hot tubes are more visible in regions of lower matter density present at larger η's [9, 10].

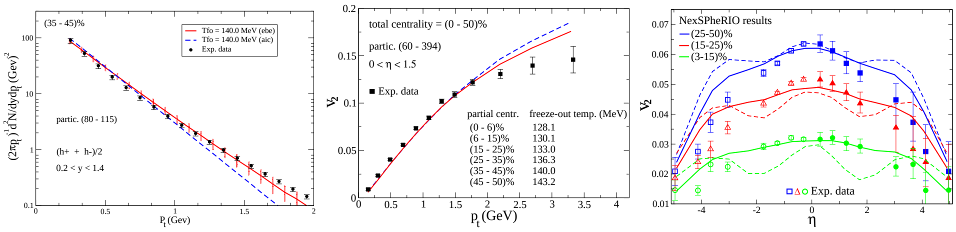

Fig. 2. Left: charged particle p_t distribution. Solid line: e-by-e initial conditions. Dashed: smooth initial conditions. Data: [12]. Center: p_t dependence of $\langle v_2 \rangle$. Data: [13]. Right: η dependence of $\langle v_2 \rangle$. Data: [13].

2.3. Other comparisons

In [14], we argued that the hot tubes should manifest themselves giving smaller HBT radii. However, the situation might be more complicated.

Another observable where hot tubes might manifest themselves is the ridge, a structure observed in the 2 particle correlations, plotted as function of pseudorapitity difference $\Delta\eta$ and azimutal angle difference $\Delta\phi$ between a high p_t trigger hadron and its associated hadrons (see *e.g.* [15]). The structure is $\Delta\eta$ independent. In NeXSPheRIO, the hot tubes can lead to such a ridge for the e-by-e initial conditions and not the smooth ones [16].

Finally, the fluctuations in the e-b-e initial conditions also manifest themselves in fluctuations of v_2 (as well as v_1). The predicted values for v_2 at 130 A GeV [17] and estimates at 200 A GeV [5] are in agreement with data [18, 19]. Improvements to remove the non-flow effects have been reported by STAR and PHOBOS, see *e.g.* [20].

3. New results on directed flow

In this section, we present some new *preliminary* results obtained with NeXSPheRIO on directed flow.

3.1. What is directed flow and what is expected

If a nucleus–nucleus collision is a number of independent nucleon–nucleon collisions, the momentum distribution is isotropic. If instead, it leads to thermalized matter in the overlap region, the momentum distribution is stretched along the impact parameter direction, v_2 is a measure of this stretching (so teaches about IC, thermalization, *etc.*). There is also the possibility that the momentum distribution be shifted/deformed towards one of the sides in the x–y plane, v_1 is a measure of this shift.

At some energy, a “wiggle” in $v_1(\eta)$ is predicted. In some microscopical models such as RQMD and UrQMD, this could be the case for nucleons at RHIC energy [21, 22]. In hydro models, this could be the case for the fluid, if a QGP phase occurs [23–26].

At SPS energy (40 A GeV and 158 A GeV), it was shown [27] that pions and protons behave oppositely. Pion directed flow as function of rapidity has no wiggle and crosses $y = 0$ with a negative slope while nucleon directed flow has no wiggle and crosses $y = 0$ with a positive slope (except perhaps at the higher energy, in the more peripheral bin, where there is a hint of wiggle).

3.2. RHIC results on directed flow

At RHIC, directed flow for charged particles is rather similar to what was obtained at SPS for pions: it crosses $\eta = 0$ with a negative slope [28–30]. This is understandable since charged particles are mostly pions, the fluid directed flow must be dominated by pions. The turnover in $v_1(\eta)$ occurs for different values of η in PHOBOS and in STAR (see below).

Results for identified particles are becoming available [31].

In addition, comparison of results for directed flow in Cu+Cu and Au+Au collisions show no system-size dependence [30].

3.3. NeXSPheRIO results on directed flow

NeXSPheRIO results are in qualitative agreement with PHOBOS for all η's and quantitative agreement for $|\ \eta\ | < 3$ (Fig. 3 (left)). They are in qualitative agreement with STAR for $|\ \eta\ | < 3$ but turnover occurs for smaller η than for STAR (Fig. 3 (right)).

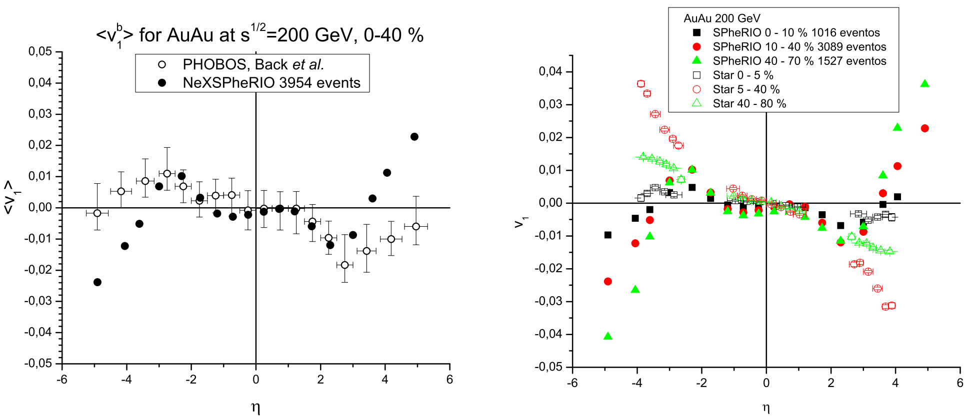

Fig. 3. Comparison of charged particle $\langle v_1 \rangle$ for NeXSPheRIO with (left) PHOBOS [28] and (right) STAR [30].

$v_1(\eta)$ from NeXSpheRIO for various centrality windows for Au+Au and Cu+Cu at 200 A GeV is shown in Fig. 4. Little dependence on A is seen in the windows 6–15% to 45–55%. Statistics must be improved.

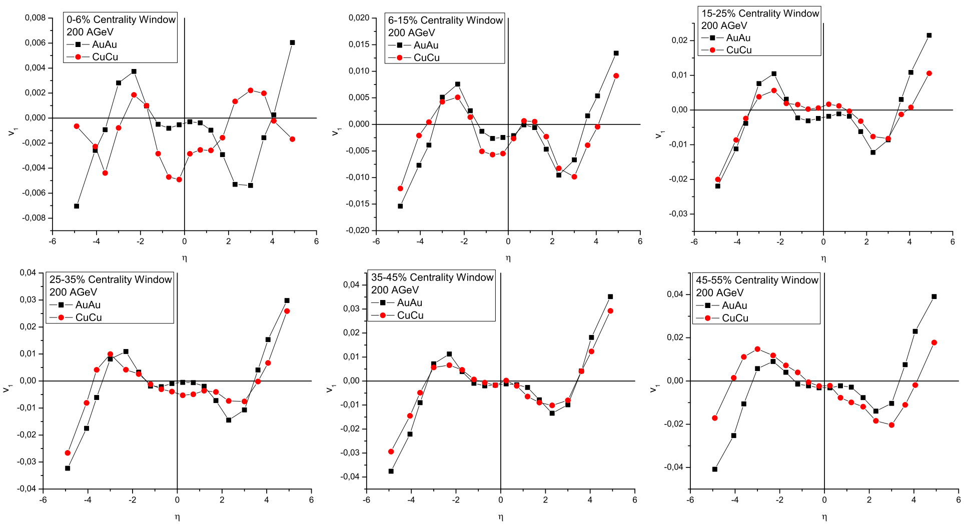

Fig. 4. Comparison of $\langle v_1 \rangle$ obtained in Cu+Cu and Au+Au, from NeXSPheRIO.

Fig. 5 (left) illustrates particle dependence. In NeXSPheRIO, protons have a big wiggle, pions have a plateau (left). A similar result was obtained using UrQMD [22]. In Fig. 5 (right), it is seen that $v_1(\eta)$ has a plateau for fluctuating initial conditions and a somewhat stronger negative inclination for smooth initial conditions.

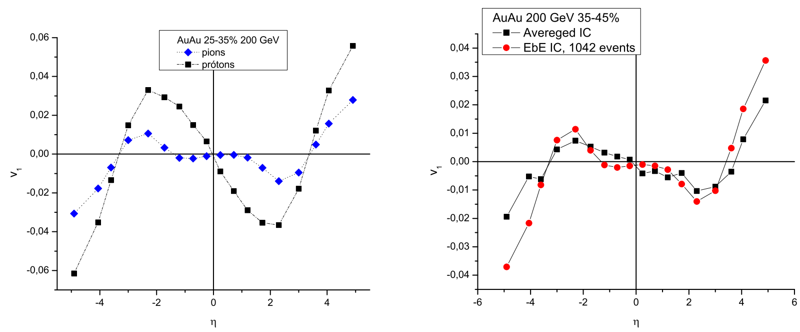

Fig. 5. Left: $\langle v1 \rangle$ for pions and protons. Right: $\langle v_1 \rangle$ for e-by-e and smooth initial conditions.

4. Summary

A short review of possible effects of fluctuating initial conditions, rather than smooth ones, was presented. In addition to providing a reasonable description of various observables, as is possible with smooth initial conditions, some new effects were listed, most notably the ridge effect and the v_2 fluctuations, which do not appear when using the smooth initial conditions.

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