Fluctuations and initial state granularity in heavy ion collisions and their effects on observables from hydrodynamics *

R.P.G. Andrade, A.L.V.R. dos Reis, F.Grassi, Y.Hama, W.L. Qian

Instituto de Física-Universidade de São Paulo

AND

T.Kodama

Instituto de Física-Universidade Federal do Rio de Janeiro

AND

J.-Y.Ollitrault

Institut de Physique Théorique-Saclay

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

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Particle Hydrodynamics, originally developed in astrophysics and adapted to relativistic heavy ion collisions in [3]. The version of NeXSPheRIO used here has initial conditions provided by NeXus [4] and normalized by an $\eta$-dependent factor to reproduce $dN_{ch}/d\eta$ in each centrality window [5]. The equation of state has a critical point [6]. $T_{f.out}$ is fixed (mostly) by $dN_{ch}/p_t dp_t$ 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].

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. $p_t$ distribution

As can be seen in figure 2 (left), the high $p_t$ part is lifted. This is expected since hot tubes must expand more violently, producing more high $p_t$ particles [9, 10].

2.2. elliptic flow

$v_2(p_t)$ is flatter as seen in figure 2 (centre). This is also expected as the isotropic expansion of hot tubes produces more high $p_t$ particles and lowers $v_2(p_t)$ [9, 10]. In addition, $v_2(\eta)$ has no shoulder [11] as seen in figure 2.
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: $\eta$ dependence of $\langle v_2 \rangle$. Data: [13].

(right). The effects (isentropic expansion) of the hot tubes are more visible in regions of lower matter density present at larger $\eta$'s [9, 10].

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 pseudorapidity difference $\Delta \eta$ and azimuthal 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 \(^{[23,24,25,26]}\).

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 \(^{[28,29,30]}\). 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 \( \eta \) 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 \( \eta \)'s and quantitative agreement for \( |\eta|<3 \) (figure 3 left). They are in qualitative agreement with STAR for \( |\eta|<3 \) but turnover occurs for smaller \( \eta \) than for STAR (figure 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 NeXSphero for various centrality windows for Au+Au and Cu+Cu at 200 A GeV is shown in figure 4. Little dependence on A is seen in the windows 6-15% to 45-55%. Statistics must be improved.

Figure 5 (left) illustrates particle dependence. In NeXSPhero, protons have a big wiggle, pions have a plateau (left). A similar result was obtained using UrQMD [22]. In figure 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.

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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