**Elliptic flow at RHIC with NeXSPheRIO**

**Abstract**  Elliptic flow at RHIC is computed event-by-event with NeXSPheRIO. Reasonable agreement with experimental results on $v_2(\eta)$ is obtained. Various effects are studied as well: reconstruction of impact parameter direction, freeze-out temperature, equation of state (with or without crossover), emission mechanism.

**Key words**  elliptic flow • relativistic heavy-ion collisions • quark-gluon plasma

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**Motivation**

Hydrodynamics seems a correct tool to describe RHIC collisions, however $v_2(\eta)$ is not well reproduced as shown by Hirano et al. [13, 15]. These authors suggested that this might be due to lack of thermalization. Heinz and Kolb [12] presented a model with partial thermalization and obtained a reasonable agreement with data. The question addressed in this work is whether lack of thermalization is the only explanation for this disagreement between data and theory for $v_2(\eta)$.

**Brief description of NeXSPheRIO**

The tool we use is the hydrodynamical code called NeXSPheRIO. It is a junction of two codes. The SPheRIO code is used to compute the hydrodynamical evolution. It is based on smoothed particle hydrodynamics, a method originally developed in astrophysics and adapted to relativistic heavy-ion collisions [2]. Its main advantage is that any geometry in the initial conditions can be incorporated. The NeXus code is used to compute the initial conditions $T_{\mu\nu}, J^\mu, u^\mu$ and on a proper time hypersurface [5, 11]. An example of initial condition for one event is shown in Fig. 1.

NeXSPheRIO is run many times, corresponding to many different events or initial conditions. In the end, an average over final results is performed. This mimics experimental conditions. This is different from the canonical approach in hydrodynamics where initial conditions are adjusted to reproduce some selected data and are very smooth.

This code has been used to study a range of problems concerning relativistic nuclear collisions: effect of fluctuating initial conditions on particle distributions [1],...
energy dependence of the kaon effective temperature [6], interferometry at RHIC [16], transverse mass distributions at SPS for strange and non-strange particles [9].

**Results**

**Theoretical vs. experimental computation**

Theoretically, the impact parameter angle $\phi_b$ is known. The elliptic flow can be computed easily through

$$\langle v_2 \rangle = \left( \frac{\int dN/d\phi \cos[2(\phi - \phi_b)] d\phi}{\int dN/d\phi d\phi} \right)$$

The average is performed over all events in the centrality bin. This is shown by the lowest solid curve in Fig. 2.

Experimentally, the impact parameter angle $\psi_2$ is reconstructed and a correction is applied to the elliptic flow computed with respect to this angle, to correct for the reaction plane resolution. For example, in a Phobos-like way [3, 4]

$$\langle v_2 \rangle = \left( \frac{\int dN/d\psi \cos[2(\psi - \psi_2)] d\psi}{\int dN/d\psi d\psi} \right)$$

$$\psi_2 = \frac{1}{2} \tan^{-1} \left( \sum_i \sin 2\phi_i / \sum_i \cos 2\phi_i \right)$$

where $\psi_2^{00}$ and $\psi_2^{-0}$ are determined.
for subevents $\eta < 0$ and $\eta > 0$, respectively and if $v_2$ is computed for a positive (negative) $\eta$, the sum in $\eta_2$, Eq. (3), is over particles with $\eta < 0$ ($\eta > 0$).

In the track-based method, $v_2^{\eta_1}$ and $v_2^{\eta_2}$ are determined for subevents $2.05 < |\eta| < 3.2$ and $v_2$ is obtained for particles around $0 < \eta < 1.8$ and reflected (there is also an additional $\sqrt{2}$ in the reaction plane correction in Eq. (2)).

In Fig. 2, we also show the results for $v_2$ without the reaction plane resolution correction (right-most term in right hand side of Eq. (2)) for both the hit-based (dashed line) and track-based (dotted line) methods. We see that both curves lie above the true (solid) curve, so dividing them by a cosine will not improve them. Therefore, in the following we use the theoretical method to make further comparisons.

Effect of $T_{\text{freeze-out}}$

In all comparisons, the same set of initial conditions is used, scaled to reproduce $dN/d\eta$ for a given $T_{\text{freeze-out}}$. In Fig. 3, the pseudorapidity and transverse momentum distributions as well as $v_2(\eta)$ are shown for two freeze-out temperatures. $v_2(\eta)$ and $dN/dp_t$ favor $T_{\text{freeze-out}} = 135$ MeV, so this temperature is used thereafter.

Effect of the equation of state

We compare results obtained for a quark matter equation of state with first order transition to hadronic matter and with a crossover as shown in Fig. 4 (for details see [10]).

We have checked that the $\eta$ and $p_t$ distributions are not much affected. We expect larger $v_2$ for crossover because there is always acceleration and this is indeed what is seen in Fig. 5.

Effect of emission mechanism

We compare results obtained for freeze-out and continuous emission [7, 8]. Again, we have checked that the $\eta$ and $p_t$ distributions are not much affected. We expect earlier emission, with less flow, at large $|\eta|$ regions, therefore, narrower and this is indeed what is seen in Fig. 6.

Effect of initial conditions

Compared to Hirano’s pioneering work with smooth initial conditions, the fact that we used event-by-event initial conditions seems crucial; we immediately

![Fig. 4. Sketch of the first order phase transition diagram (top) and diagram with critical point (bottom).](image)

![Fig. 5. Comparison of $v_2(\eta)$ for first order transition (I OPT) and critical point (CP) equations of state.](image)

![Fig. 6. Comparison of $v_2(\eta)$ for freeze-out (FO) and continuous emission (CE).](image)
avoid the two bump structure. To check this, it is interesting to study what we would get with smooth initial conditions. We obtained such conditions by averaging the initial conditions of 30 NeXus events. Again, we have checked that the $\eta$ and $p_t$ distributions are not much affected but preliminary results indicate that now $v_2$ is very different, having a bumpy structure as shown in Fig. 7.

**Summary**

$v_2(\eta)$ was computed with NeXSPheRIO at RHIC energy. Event-by-event initial conditions seem important to get the right shape of $v_2(\eta)$ at RHIC. Other features seem less important: reconstruction of impact parameter direction, freeze-out temperature, equation of state (with or without crossover), emission mechanism. Lack of thermalization is not necessary to reproduce $v_2(\eta)$. The fact that there is thermalization outside mid-pseudorapidity is reasonable given that the (averaged) initial energy density is high there (figure not shown). A somewhat similar conclusion was obtained by Hirano [14], using color glass condensate initial conditions for a hydrodynamical code and emission through a cascade code.

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**References**