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Elliptic flow at RHIC with NeXSPheRIO

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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 explaination 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],

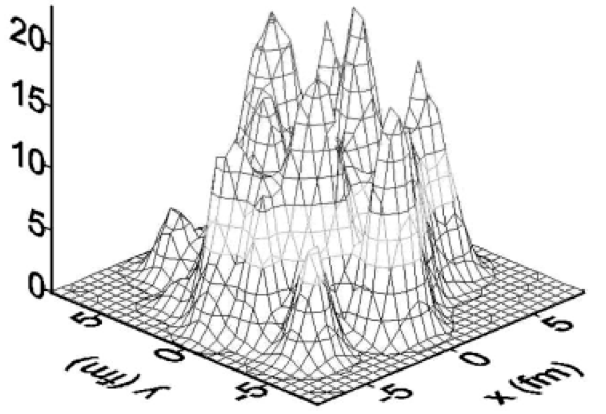

Fig. 1. An example of initial energy density in the $\eta = 0$ plane.

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 ϕ_b is known. The elliptic flow can be computed easily through

$$\langle v_2 \rangle = \left\langle \frac{\int dN/d\phi \cos\left[2(\phi-\phi_b)\right] d\phi}{\int dN/d\phi\, d\phi} \right\rangle \tag{1}$$

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 ψ_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]

$$\langle v_2 \rangle = \frac{\sum_i dN/d\phi_i \cos\left[2(\phi_i-\psi_2)\right]}{\sum_i dN/d\phi_i} \times \frac{1}{\sqrt{\left\langle \cos\left[2\left(\psi_2^{<0}-\psi_2^{>0}\right)\right]\right\rangle}} \tag{2}$$

where

$$\psi_2 = \frac{1}{2}\tan^{-1}\frac{\sum_i \sin 2\phi_i}{\sum_i \cos 2\phi_i} \tag{3}$$

In the hit-based method, $\psi_2^{<0}$ and $\psi_2^{>0}$ are determined

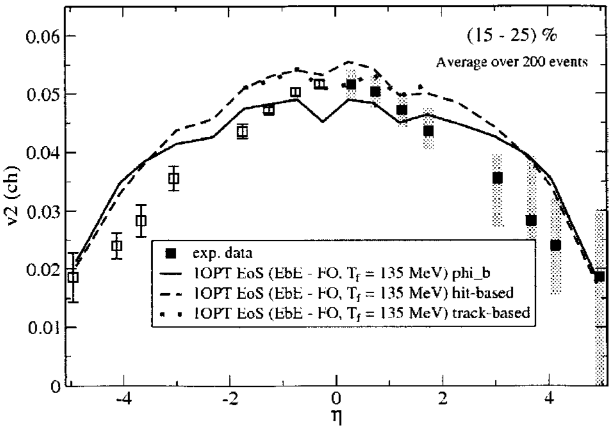

Fig. 2. Comparison of various ways of computing v_2: solid line is using the known impact parameter angle ϕ_b, dashed and dotted lines is using the reconstructed impact parameter angle v_2. 1OPT stands for equation of state with first order transition, EbE, event-by-event calculation, FO, freeze-out mechanism for particle emission. Data are from Phobos [3, 4]. For more details see the text.

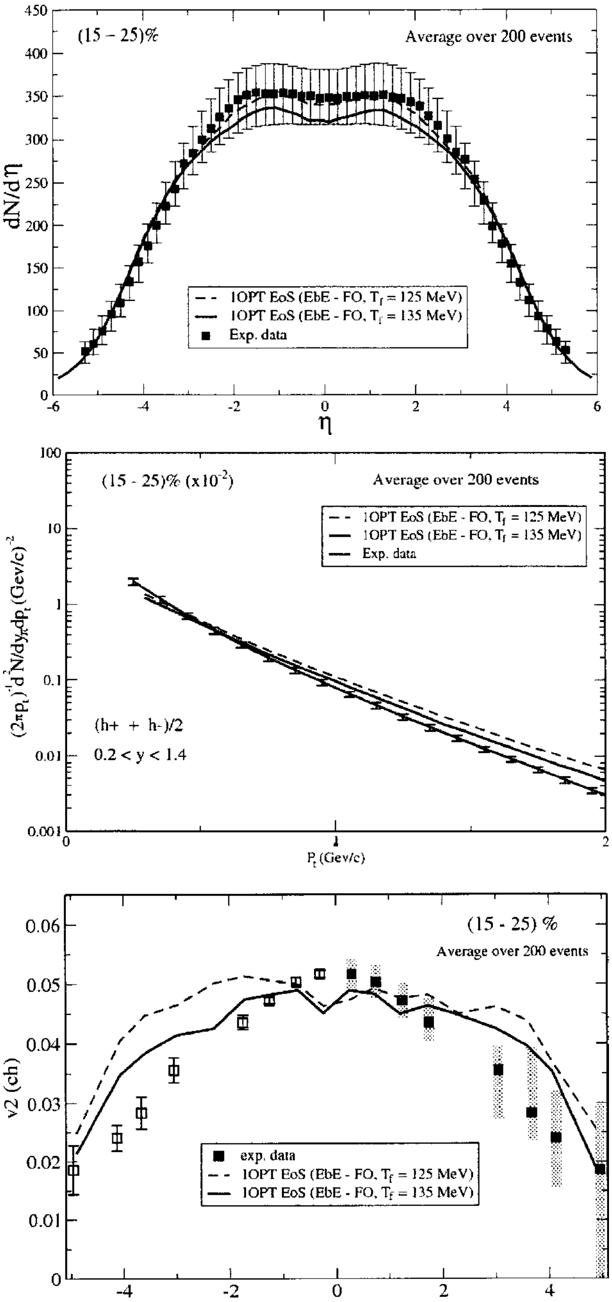

Fig. 3. Comparison of $dN/d\eta$, $dN/p_t dp_t$ and v_2 for two freeze-out temperatures. Abbreviations: see Fig. 2.

for subevents $\eta < 0$ and $\eta > 0$, respectively and if v_2 is computed for a positive (negative) η, the sum in η_2, Eq. (3), is over particles with $\eta < 0$ ($\eta > 0$).

In the track-based method, $\psi_2^{<0}$ and $\psi_2^{>0}$ 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 $T_{f_{out}}$

In all comparisons, the same set of initial conditions is used, scaled to reproduce $dN/d\eta$ for a given $T_{f_{out}}$. 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 $dN/p_t dp_t$ favor $T_{f_{out}} = 135$ MeV, so this temperature is used thereafter.

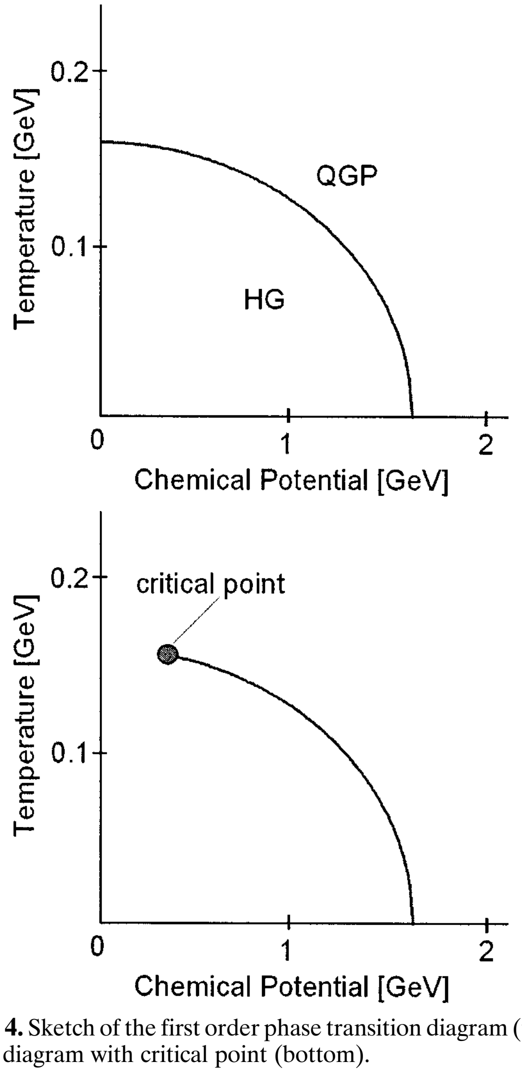

Fig. 4. Sketch of the first order phase transition diagram (top) and diagram with critical point (bottom).

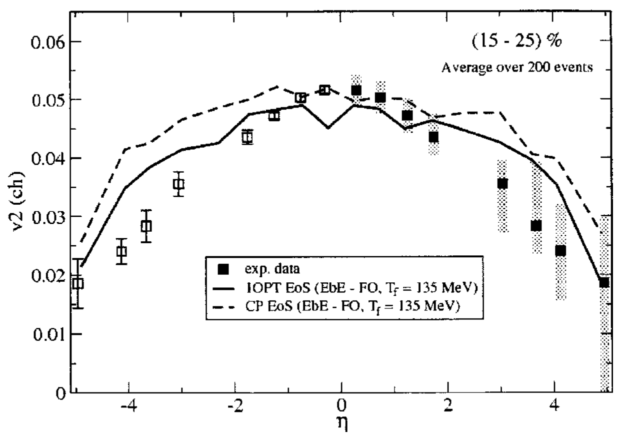

Fig. 5. Comparison of $v_2(\eta)$ for first order transition (1OPT) and critical point (CP) equations of state.

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 η 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 η 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

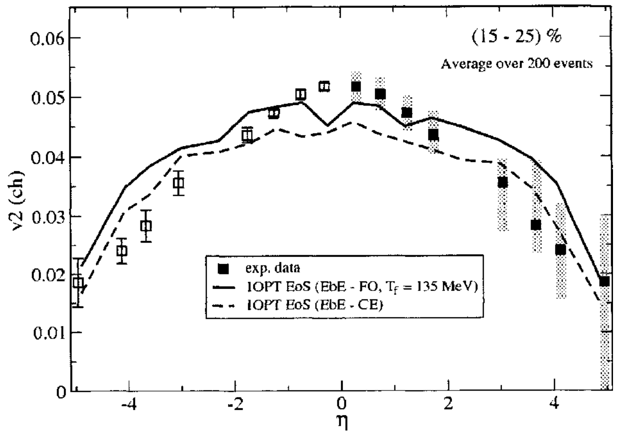

Fig. 6. Comparison of $v_2(\eta)$ for freeze-out (FO) and continuous emission (CE).

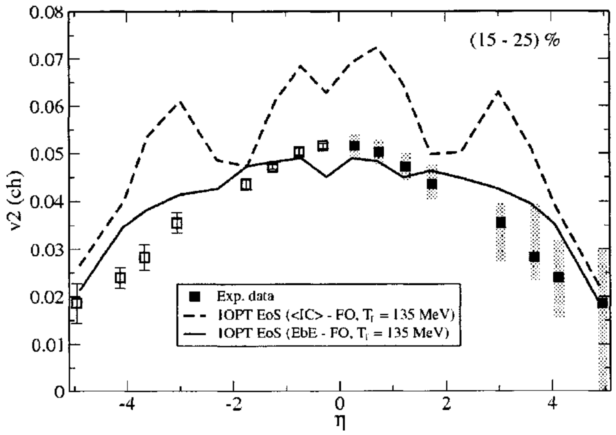

Fig. 7. Comparison of computed event-by-event (EbE) and with smooth initial conditions (⟨IC⟩).

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 η 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-pseudo-rapidity 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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