Anisotropic flow decorrelation in heavy-ion collisions at RHIC-BES energies with 3D event-by-event viscous hydrodynamics

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In the RHIC Beam Energy Scan program, gold nuclei are collided with different collision energies in the range from few to 62.4 GeV. The goals of the program are to explore the onset of QGP creation, locate the critical point of QCD and study dense baryon matter. We report on the first application of Monte Carlo Glauber (GLISSANDO2) and T_RENTo $p = 0$ initial states extended to 3D for event-by-event viscous fluid dynamic (vHLLE) with hadronic cascade modelling of Au+Au collisions at $\sqrt{s_{NN}} = 27$ and 62.4 GeV, which is the upper region of RHIC BES energies. The initial states are extended into both the longitudinal direction and for finite baryon density using simple ansätze. The full energy and baryon charge counting in the initial states is implemented. We show the reproduction of elliptic flow, at both collision energies and with both initial states. We compare it also to the results obtained with UrQMD initial state. Furthermore, we show the results for rapidity decorrelation of elliptic flow r_2 at $\sqrt{s_{NN}} = 27$ and 200 GeV from the same setup of hydrodynamic calculations with the 3D Monte Carlo Glauber and UrQMD initial states. We discuss the features of the initial states responsible for the magnitude of the observed flow decorrelation.

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1. Introduction

For two decades, investigations of anisotropic flows taught us much about the quark-gluon plasma, but most of the studies focused on the flow in the transverse plane at midrapidity. However, studying event-by-event fluctuations along the longitudinal direction may help us understand the transport properties of quark-gluon plasma. At RHIC-BES energies, the decorrelation of the flow anisotropy along the longitudinal direction is just starting to be researched. So far, there are only preliminary results from STAR at $\sqrt{s_{\mathrm{NN}}} = 27$ and 200 GeV [1, 2]. This paper summarizes the first calculation of a kind at RHIC-BES energy in a hydrodynamic model [3].

2. Model

For the calculations a hybrid event-by-event viscous hydrodynamic model is used. It consists of four parts. It starts with three-dimensional initial state. Here, we worked with three different models: UrQMD [4], which uses PYTHIA6 to simulate inelastic nucleon-nucleon scatterings through string formation and subsequent string break-up, GLISSANDO2 [5], which is a Monte Carlo Glauber model, and T$_R$ENTo [6], which introduces a generalized ansatz for the entropy density deposition from the participant nucleons. Since Glissando and T$_R$ENTo only provide the initial state in the transverse plane, we extended them to longitudinal direction following [7]. Moreover, we fixed the total energy and baryon charge to those of participants and therefore there is one less parameter to tune. The hydrodynamic stage of evolution is modelled with a hydrodynamic code vHLLE [8], in which we included the shear viscosity. Next, a Monte Carlo hadron sampling is performed according to Cooper-Frye formula. The final step of the model is to simulate hadronic rescatterings and resonance decays of the sampled hadrons using UrQMD cascade. The model also includes a finite baryon and electric charge density at all stages and it is important, because we are doing simulations at relatively low energies. More detailed description of the model can be found in [9].

3. Flow

The classical definition of the anisotropic flow is through a Fourier series of p_T distribution:

$$v_n = \frac{\int \mathrm{d}\phi \cos(n(\phi - \Psi_n)) \frac{\mathrm{d}^3 N}{p_T \mathrm{d}p_T \mathrm{d}y \mathrm{d}\phi}}{\int \mathrm{d}\phi \frac{\mathrm{d}^3 N}{p_T \mathrm{d}p_T \mathrm{d}y \mathrm{d}\phi}}. \tag{1}$$

There are several methods to calculate anisotropic flow from experimental or simulated data, from which the event plane (EP) method and the 2-particle cumulant method were used for this work. Figure 1 shows the centrality dependence of the p_T integrated elliptic and triangular flow. From this figure we can see that T$_R$ENTo IS produces the largest anisotropic flow, whereas GLISSANDO IS produces the lowest v_2 and v_3. In the non-central collisions at 27 GeV as well as in all considered centrality classes at 62.4 GeV, calculations with T$_R$ENTo IS have the best agreement with the experimental data for elliptic flow. However, p_T dependent elliptic flow (Figure 2) shows that our calculations are in agreement with the data only for $p_T < 1$ GeV. At larger p_T, all of the initial states start to underpredict the data.
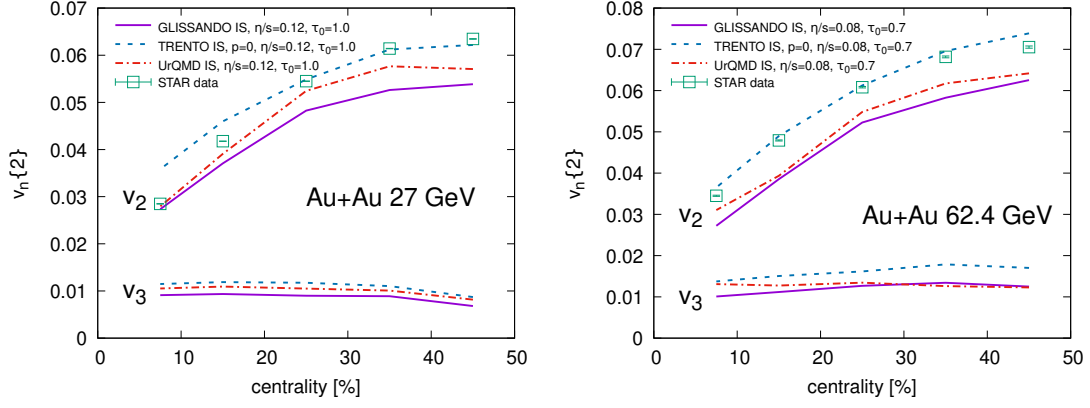
Figure 1: Elliptic and triangular flows of charged hadrons as functions of centrality for $\sqrt{s_{\mathrm{NN}}} = 27$ (left) and 62.4 GeV (right) calculated using 2-particle cumulant method compared with STAR data [10, 11].
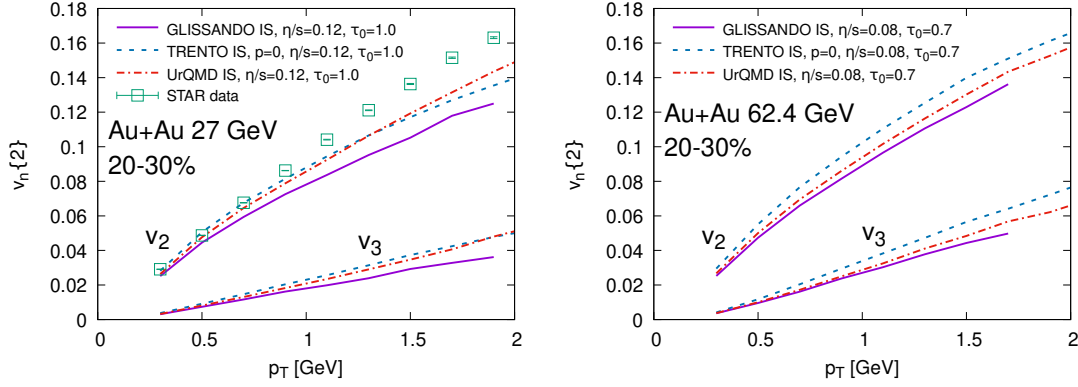
Figure 2: Elliptic and triangular flows of charged hadrons as functions of p_T for $\sqrt{s_{\mathrm{NN}}} = 27$ (left) and 62.4 GeV (right) calculated using 2-particle cumulant method compared with STAR data [10].
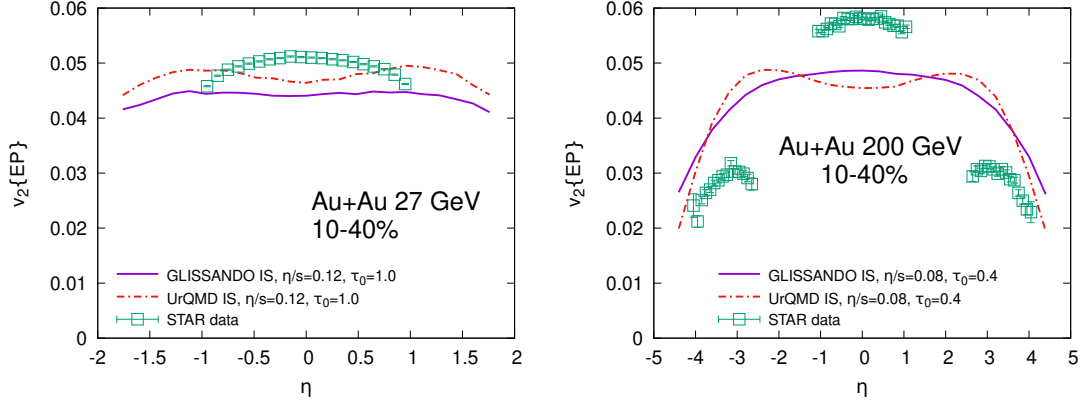
Figure 3 shows the elliptic flow as a function of pseudorapidity. At 27 GeV, GLISSANDO and UrQMD initial states reproduce overall order of magnitude of the elliptic flow, but underestimate its value at mid-rapidity, which is consistent with previous figures. At 200 GeV the experimental data indicate a triangular pseudorapidity dependence that neither of the initial states can describe.

4. Decorrelation

The longitudinal fluctuations leads to decorrelation of anisotropic flows along the pseudorapidity direction. Using the definition of the flow vector $\mathbf{V}_n = v_n e^{in\Psi_n}$, the longitudinal decorrelation can be expressed using the factorization ratio:

$$r_n(\eta, \eta_{\mathrm{ref}}) = \frac{\langle \mathbf{V}_n(-\eta)\mathbf{V}_n^*(\eta_{\mathrm{ref}}) \rangle}{\langle \mathbf{V}_n(+\eta)\mathbf{V}_n^*(\eta_{\mathrm{ref}}) \rangle} = \frac{\langle v_n(-\eta)v_n(\eta_{\mathrm{ref}}) \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{\mathrm{ref}})) \rangle}{\langle v_n(+\eta)v_n(\eta_{\mathrm{ref}}) \cos n(\Psi_n(+\eta) - \Psi_n(\eta_{\mathrm{ref}})) \rangle}. \quad (2)$$

If the factorisation ratio is equal to 1, it means that the flow vectors at $+\eta$ and $-\eta$ are fully correlated, and when it gets below 1, we got a decorrelation between flow vectors at $\pm\eta$. From Eq. (2) it
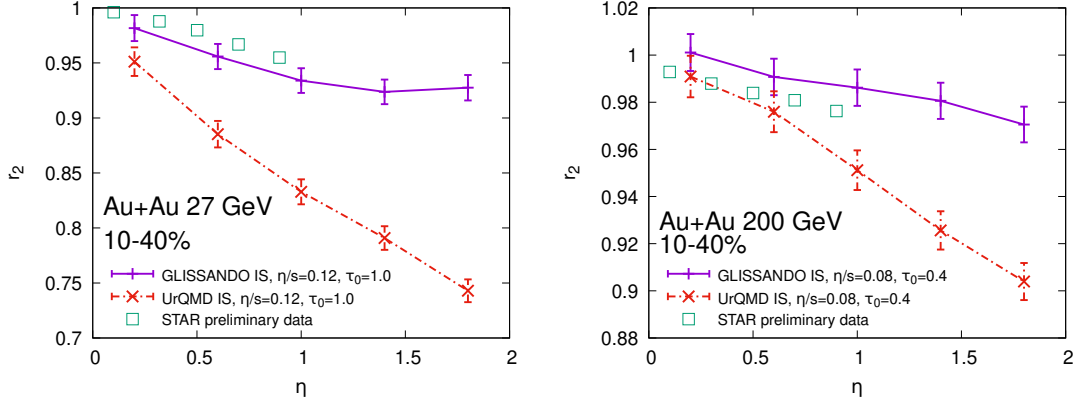
Figure 3: Elliptic flow of charged hadrons as a function of pseudorapidity for $\sqrt{s_{\mathrm{NN}}} = 27$ (left) and 200 GeV (right) calculated using EP method compared with STAR data [10, 12].

can be seen that the flow decorrelation may be caused by two separate effects: flow magnitude decorrelation and flow angle decorrelation. Thus we can define corresponding factorisation ratios:

$$r_n^v(\eta) = \frac{\langle v_n(-\eta)v_n(\eta_{\mathrm{ref}})\rangle}{\langle v_n(+\eta)v_n(\eta_{\mathrm{ref}})\rangle}, \tag{3a}$$

$$r_n^\Psi(\eta) = \frac{\langle \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{\mathrm{ref}}))\rangle}{\langle \cos n(\Psi_n(+\eta) - \Psi_n(\eta_{\mathrm{ref}}))\rangle}. \tag{3b}$$

Figure 4 shows the factorisation ratio as a function of pseudorapidity. We did not use the extended T_RENTo IS for these calculations, since it does not have implemented any tilt in the longitudinal direction and thus the factorisation ratio would be equal to 1. At 27 GeV, the model with UrQMD initial state shows much stronger decorrelation then the one seen in the data. On the other hand, calculations with GLISSANDO initial state can describe the experimental data within uncertainties for both energies.

Figure 4: Factorization ratio r_2 of charged hadrons as a function of pseudorapidity for $10 - 40\%$ Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 27$ (left) and 200 GeV (right) compared with STAR preliminary data [1, 2].

Figure 5 shows contributions of the flow angle and flow magnitude decorrelation separately for 27 GeV. It can be seen that for both models the flow angle decorrelation plays more important

role than the flow magnitude decorrelation. The same hierarchy has been observed in calculations at LHC energies [13].
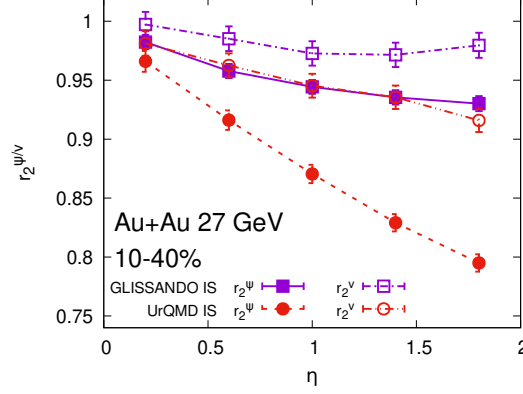
Figure 5: The flow magnitude r_2^v and the flow angle decorrelation r_2^Ψ of charged hadrons as a function of pseudorapidity for $10 - 40\%$ Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 27$ GeV.

It is well known that the anisotropic flow coefficients are strongly correlated with the initial state eccentricities. Therefore, to better understand the big difference between the initial state models, we can define the factorisation ratio of initial-state eccentricities:

$$r_n^\epsilon(\eta_s) = \frac{\left\langle \epsilon_n(-\eta_s)\epsilon_n(\eta_{s,\mathrm{ref}}) \cos[n\left(\Psi_n(-\eta_s) - \Psi_n(\eta_{s,\mathrm{ref}})\right)] \right\rangle}{\left\langle \epsilon_n(\eta_s)\epsilon_n(\eta_{s,\mathrm{ref}}) \cos[n\left(\Psi_n(\eta_s) - \Psi_n(\eta_{s,\mathrm{ref}})\right)] \right\rangle} \tag{4}$$

where

$$\epsilon_n e^{in\Psi_n} = \frac{\int e^{in\phi} r^n \rho(\vec{r}) d\phi\, r\, dr}{\int r^n \rho(\vec{r}) d\phi\, r\, dr}$$

This factorisation ratio as a function of space-time rapidity is shown in Figure 6. Comparison with the flow decorrelation (Figure 4) shows that the two factorisation ratios agree even quantitatively, which means that longitudinal decorrelation is created in the initial state.
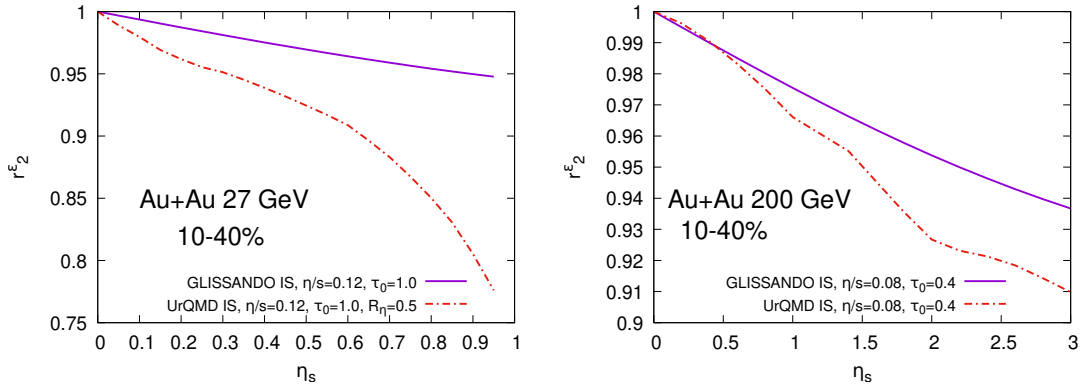
Figure 6: Longitudinal decorrelation of the initial state eccentricity ϵ_2 as a function of space-time rapidity for $10 - 40\%$ Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 27$ (left) and 200 GeV (right).

5. Conclusions

This paper presents the elliptic flow and the flow decorrelation in Au-Au collisions at RHIC-BES energies simulated with the help of 3D viscous hydrodynamic model with three different initial state alternatives, which is a first simulations with this kind of hydrodynamic model at these energies. The best description of the data at midrapidity has been provided by the model with T$_R$ENTo initial state with parameter $p = 0$. We found that the flow decorrelation is mainly caused by the decorrelation of the flow angle, which has been seen also at LHC energies. We also showed that the strong decorrelation of the model with UrQMD IS is caused by strong decorrelation of initial-state eccentricity.

References

[1] M. Nie [STAR collaboration], Nucl. Phys. A **982** (2019), 403-406

[2] M. Nie [STAR collaboration], Nucl. Phys. A **1005** (2021), 121783

[3] J. Cimerman *et al.*, Phys. Rev. C **104**, 014904 (2021)

[4] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255-369 (1998)

[5] M. Rybczynski *et al.*, Comput. Phys. Commun. **185**, 1759-1772 (2014)

[6] J. S. Moreland, J. E. Bernhard and S. A. Bass, Phys. Rev. C **92**, 011901 (2015)

[7] P. Bozek and W. Broniowski, Phys. Rev. C **85**, 044910 (2012)

[8] I. Karpenko, P. Huovinen and M. Bleicher, Comput. Phys. Commun. **185**, 3016-3027 (2014)

[9] J. Cimerman *et al.*, Phys. Rev. C **103**, 034902 (2021)

[10] L. Adamczyk *et al.* [STAR collaboration], Phys. Rev. C **86**, 054908 (2012)

[11] L. Adamczyk *et al.* [STAR collaboration], Phys. Rev. C **98**, 034918 (2018)

[12] B. I. Abelev *et al.* [STAR collaboration], Phys. Rev. C **77**, 054901 (2008)

[13] P. Bozek and W. Broniowski, Phys. Rev. C **97**, 034913 (2018)